ERDC/CHL TR-11-1

Coastal and Hydraulics Laboratory

US Army Corps of Engineers®
Engineer Research and Development Center

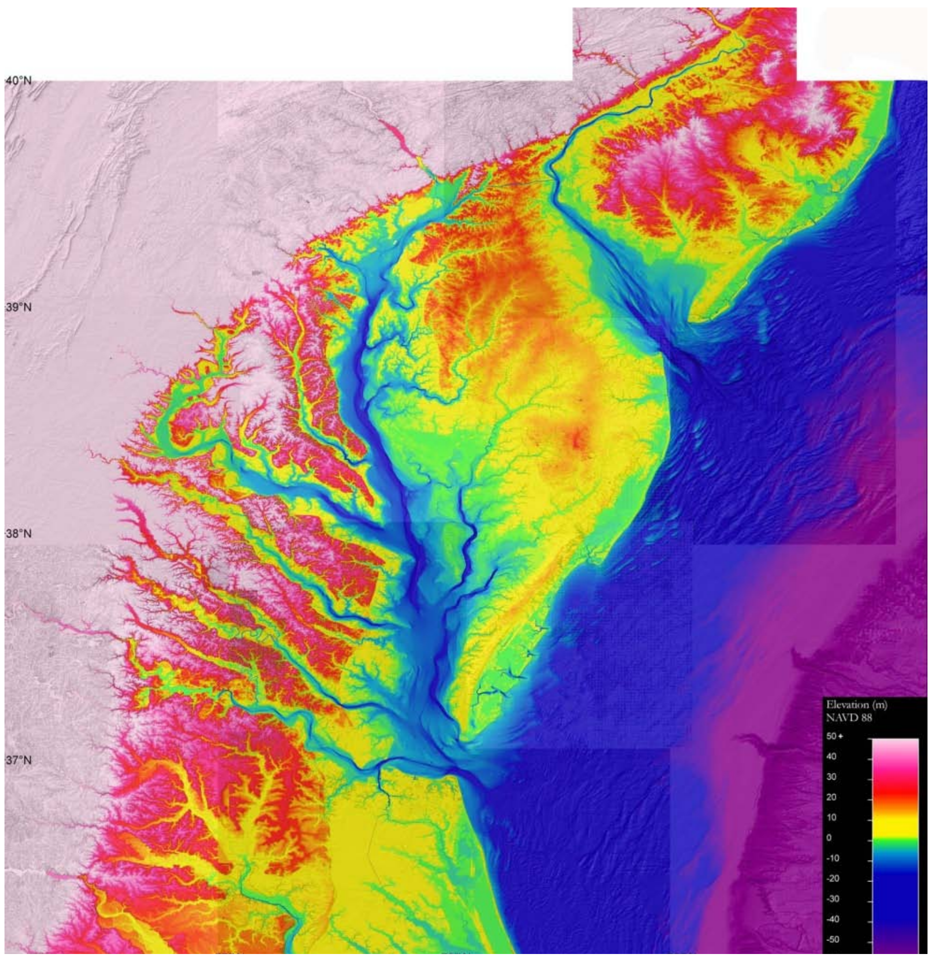
FEMA Region III Storm Surge Study

Coastal Storm Surge Analysis System Digital Elevation Model

Report 1: Intermediate Submission No. 1.1

Michael F. Forte, Jeffrey L. Hanson, Lisa Stillwell,
Margaret Blanchard-Montgomery, Brian Blanton,
Rick Luettich, Hugh Roberts, John Atkinson, and Jason Miller

March 2011



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Report 1: Intermediate Submission No. 1.1

Michael F. Forte, Jeffrey L. Hanson

Field Research Facility
U.S. Army Engineer Research and Development Center
1261 Duck Rd.
Kitty Hawk, NC 27949

Lisa Stillwell, Margaret Blanchard-Montgomery, Brian Blanton

Renaissance Computing Institute
100 Europa Drive, Suite 540
Chapel Hill, NC 27517

Rick Luettich

University of North Carolina
Institute of Marine Sciences
3431 Arendell St
Morehead City, NC 28557

Hugh Roberts, John Atkinson

ARCADIS
4999 Pearl East Circle, Suite 200
Boulder, CO 80301

Jason Miller

Philadelphia District
US Army Corps of Engineers
Wanamaker Bldg, 100 Penn Square East, Philadelphia, PA 19107

Report 1 of a series

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Washington, DC 20314-1000

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Abstract: The Federal Emergency Management Agency, Region III office, has initiated a study to update the coastal storm surge elevations within the states of Virginia, Maryland, and Delaware, and the District of Columbia including the Atlantic Ocean, Chesapeake Bay and its tributaries, and the Delaware Bay. This effort is one of the most extensive coastal storm surge analyses to date, encompassing coastal floodplains in three states and including the largest estuary in the world. The study will replace outdated coastal storm surge stillwater elevations for all Flood Insurance Studies in the study area, and serve as the basis for new coastal hazard analysis and ultimately updated Flood Insurance Rate Maps (FIRMs). Study efforts were initiated in August of 2008, and are expected to conclude in 2010.

The storm surge study will utilize the Advanced Circulation Model for Oceanic, Coastal and Estuarine Waters (ADCIRC) for simulation of 2-dimensional hydraulics. ADCIRC will be coupled with 2-dimensional wave models to calculate the combined effects of surge and wind-induced waves. A seamless modeling grid was developed to support the storm surge modeling efforts. This report, the first of three reports comprising the required Submittal 1 documentation, provides a detailed overview of the construction of the Digital Elevation Model, modeling mesh, and the development of an integrated computational system for FEMA Region III storm surge modeling.

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Contents

Figures and Tables

Figures

Tables

Preface

This study was conducted for the Federal Emergency Management Agency (FEMA) under Project HSFE03-06-X-0023, “NFIP Coastal Storm Surge Model for Region III.” The FEMA technical monitor was Robin Danforth.

The work was performed by the Coastal Processes Branch (HF-C) of the Flood and Storm Protection Division (HF), U.S. Army Engineer Research and Development Center – Coastal & Hydraulics Laboratory (ERDC-CHL). At the time of publication, Dr. Ty V. Wamsley was Chief, CEERD-HF-C; Bruce Ebersole was Chief, CEERD-HF; and Dr. Jeffrey L. Hanson was the Project Manager. The Deputy Director of ERDC-CHL was Jose E. Sanchez and the Director was Dr. William D. Martin.

COL Kevin Wilson was the Commander and Executive Director of ERDC, and Dr. Jeffery P. Holland was the Director.

Unit Conversion Factors

Multiply	By	To Obtain
degrees (angle)	0.01745329	radians
fathoms	1.8288	meters
feet	0.3048	meters
inches	0.0254	meters
knots	0.5144444	meters per second
miles (nautical)	1,852	meters
miles (U.S. statute)	1,609.347	meters
square miles	2.589998 E+06	square meters
square yards	0.8361274	square meters
yards	0.9144	meters

1 Overview

The Federal Emergency Management Agency (FEMA) is responsible for preparing Federal Insurance Rate Maps (FIRMs) that delineate flood hazard zones in coastal areas of the United States. Under Task Order HSFE03-06-X-0023, the U.S. Army Corps of Engineers (USACE) and project partners are assisting FEMA in the development and application of a state-of-the-art storm surge risk assessment capability for the FEMA Region III domain which includes the Delaware Bay, Chesapeake Bay, District of Columbia, Delaware-Maryland-Virginia Eastern Shore, Virginia Beach, and all tidal tributaries and waterways connected to these systems. The goal is to develop and apply a complete end-to-end modeling system, with all required forcing inputs, for updating the floodplain levels for coastal and inland watershed communities. Key components of this work include:

1. Develop a high-resolution DEM for Region III, and convert this to an unstructured modeling grid, with up to 50-m horizontal resolution, for use with the production system.
2. Define the Region III storm hazard in terms of historical extratropical storms and synthetic hurricanes selected using the Joint Probability Method with Optimum Sampling (JPM-OS) (Niedoroda et al., 2010)
3. Prepare an end-to-end modeling system for assessment of Region III coastal storm surge hazards
4. Verify model accuracy on a variety of reconstructed tropical and extratropical storm events
5. Apply the modeling system to compute the 10-, 50-, 100-, and 500- year floodplain levels
6. Develop a database with Geographic Information System (GIS) tools to facilitate archiving, distribution, and analysis of the various storm surge data products

Under the direction of FEMA Region III Program Manager, Ms. Robin Danforth, USACE assembled a multi-organization partnership to meet the Region III objectives. Work on this project has made extensive use of the capabilities and technology developed for the North Carolina Floodplain Mapping Program (NCFMP). The availability of the NCFMP storm surge modeling system has resulted in a significant cost savings for FEMA Region III. Experts in the fields of coastal storm surge, wind-driven waves, GIS, and high-performance computational systems have worked together in this effort. The project partners and their primary roles are listed in Table 1.1.

Table 1.1. Expert Team.

Organization	Contacts	Primary Role(s)
US Army Engineer Research & Development Center Coastal & Hydraulics Laboratory Field Research Facility	Jeff Hanson Mike Forte Heidi Wadman	Project Manager DEM Construction Model Validations
Applied Research Associates/IntraRisk (ARA)	Peter Vickery	Simulated Hurricanes
ARCADIS	Hugh Roberts John Atkinson	DEM Construction Modeling Mesh
Elizabeth City State University	Jinchun Yuan	Web/GIS
Oceanweather Inc.	Vince Cardone Andrew Cox	Wind/Pressure Field Reconstructions
Renaissance Computing Institute (RENCI)	Brian Blanton Lisa Stillwell Kevin Gamiel	Modeling System DEM Construction Database/Web/GIS
University of North Carolina- Chapel Hill (UNC-CH)	Rick Luettich Crystal Fulcher	Science Consultant Modeling Mesh
US Army Corps of Engineers District Offices (NAP, NAO, NAB)	Jason Miller Paul Moye Jared Scott	Bathy/Topo Data Inventory

In addition to the expert team, a Technical Oversight Group provided guidance and input to all project phases. This group included members from the following organizations:

- Chesapeake Bay Research Consortium
- Delaware Flood Mitigation Program
- Federal Emergency Management Agency
- Dewberry, Inc.
- North Carolina Floodplain Mapping Program
- USACE Engineer Research and Development Center

This report (Submittal 1.1) is one of three stand-alone reports that comprise the documentation set required for Intermediate Submission No. 1 – Scoping and Data Review. The contents of each Submittal are listed in Table 1.2. Guidelines for study conduct and documentation appear in FEMA (2007).

Table 1.2. Contents of the Submittal 1 Reports.

Submittal	Title	Contents
1.1	FEMA Region III Coastal Storm Surge Analysis: Study Area and Digital Elevation Model (DEM)	Project Overview Study Area DEM Development
1.2	FEMA Region III Coastal Storm Surge Analysis: Computational System	Modeling System Mesh Development Hurricane Parameters
1.3	FEMA Region III Coastal Storm Surge Analysis: Extratropical Storm Events	Storm Selection Data Preparation

The following sections describe the dynamic Region III study area and provide details on the assembly of a state-of-the-art Digital Elevation Model (DEM) for this domain. The DEM, produced by merging the latest in coastal Lidar and other topographic survey data sets with the most reliable bathymetric datasets of the region, forms the basis for the numerical model grids. For details on the modeling system, including the associated model grids, the reader is referred to Submittal 1.2.

2 Study Area

The project study area, depicted by the red box in Figure 2.1, includes portions of North Carolina, Virginia, District of Columbia, Maryland, West Virginia, Delaware, Pennsylvania, and New Jersey. The study area also extends offshore to include the continental shelf and a portion of the deeper ocean. The high-resolution modeling is focused on the terrain and bathymetry found between the 15 meter elevation contour and the 50 meter bathymetric contour.

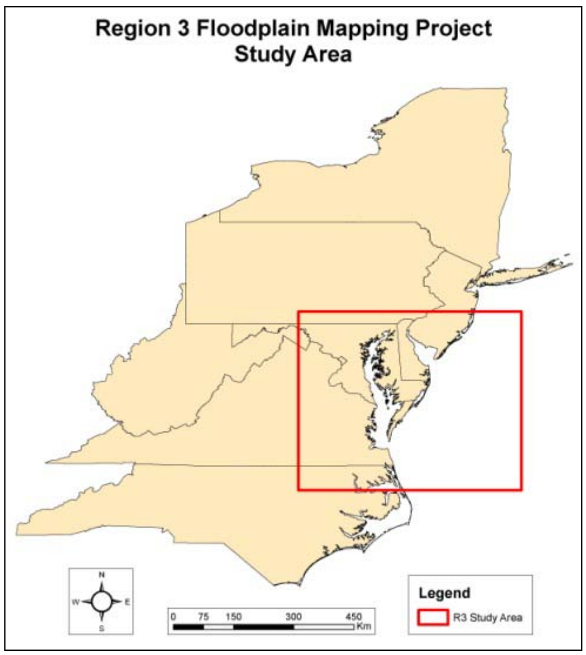

Figure 2.1. East coast US project study area (red box).

Several major metropolitan areas fall within the study domain, including (from North to South) Trenton, NJ; Camden, NJ; Philadelphia, PA; Wilmington, DE; Baltimore, MD; Annapolis, MD; Cambridge, MD; Washington DC; Alexandria, VA and Norfolk, VA. A population density map, provided by FEMA to the project team for use as guidance in the development of model resolution, appears in Figure 2.2.

The FEMA Region III domain encompasses a diverse set of land morphologies, ocean coastal environments, estuaries, rivers, and tributaries. The satellite image of Figure 2.3 highlights the diversity and complexity of coastal regions within the study area. Three primary

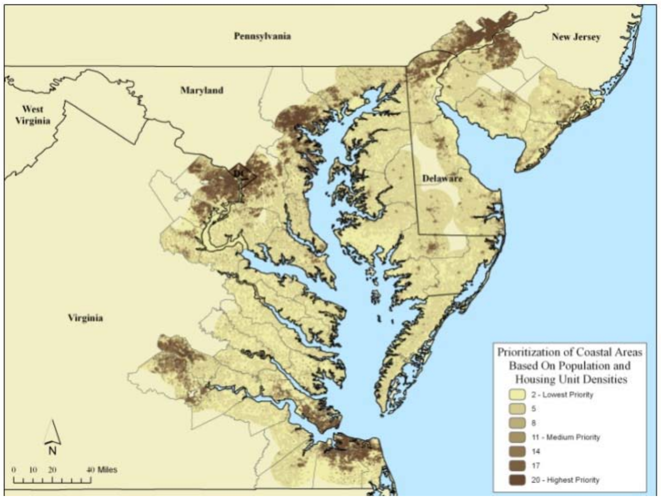

Figure 2.2. Prioritization of project effort based on population density. Map provided by FEMA.

Figure 2.3 Satellite image showing complexities of FEMA Region III coastal storm surge domain.

morphologic features influenced by tidal waters within this domain are the Delaware River/Delaware Bay complex, Delaware-Maryland-Virginia eastern shore, and Chesapeake Bay. In particular, the Delaware and Chesapeake Bays support fragile ecosystems and are of significant economic importance. Each of these estuaries is described in more detail below.

Delaware River/Bay Complex

The Delaware River is the longest un-dammed river east of the Mississippi, extending 530 kilometers from the confluence of its East and West branches at Hancock, N.Y. to the mouth of the Delaware Bay where it meets the Atlantic Ocean. The river is considered to be tidally influenced from Trenton, NJ south to where it meets the Delaware Bay and empties into the Atlantic Ocean. As depicted in Figure 2.4, tidal portions of the river are bordered by Pennsylvania, New Jersey and Delaware. The River leads into the 2025 square-kilometer Delaware Bay, which is bordered on the north by New Jersey and on the south by Delaware. The tidal reach of the Delaware River, including the Delaware Bay, has been included in the National Estuary Program, a project set up to protect estuarine systems of national significance.

Figure 2.4. Delaware River leading to the Delaware Bay and Atlantic Ocean.

There are numerous economic benefits from the river. The Delaware River Port Complex (including docking facilities in Pennsylvania, New Jersey, and

Delaware) is the largest freshwater port in the world. It is one of only 14 strategic ports in the nation transporting military supplies and equipment by vessel to support our troops overseas. The Delaware River and Bay is home to the third largest petrochemical port as well as five of the largest east coast refineries. Nearly 42 million gallons of crude oil are moved on the Delaware River on a daily basis. It is the largest North American port for steel, paper, and meat imports as well as the largest importer of cocoa beans and fruit on the east coast.

Furthermore, Delaware Bay is a wildlife resource of both local and national significance, including being one of the four most important shorebird migration sites in the world. There is a very significant recreational fishery in the Delaware Bay, with an annual harvest of Eastern oysters exceeding $1.5 million in market value and home to the world's largest population of spawning horseshoe crabs.

Chesapeake Bay

The Chesapeake Bay is largest estuary in the United States and the third largest in the world. It is approximately 322 kilometers long and runs north-south from the mouth of the Susquehanna River to the Atlantic. It has 18,670 kilometers of tidal shoreline, including tidal wetlands and islands. The tidal boundaries primarily influence Maryland, Virginia, and Washington D.C. The bay varies in width from about 5.6 kilometers near Aberdeen, MD to 50 kilometers from Smith Point, VA to the Virginia shore. The average depth of the bay is about 7 meters. As the map of Figure 2.5 reveals, there are numerous tributaries leading into the bay.

Two of the five major North Atlantic ports, Baltimore and Hampton Roads, are on the Bay. More than 500 million pounds of seafood is harvested from the Bay every year. The Bay supports 3,600 species of plant and animal life, including more than 300 fish species and 2,700 plant types.

The economic mainstays of the Chesapeake Bay region are shipbuilding and repair, ports with their import and export capabilities, a growing tourism trade, service jobs, and a strong military presence. Norfolk has the world's largest Navy base, and Portsmouth is home to the world's biggest ship-repair yard. The area is also a major port for container cargo and products such as grain, tobacco, cocoa beans and rubber. Hampton Roads, VA exports more coal and imports more cocoa beans and rubber than any other U.S. port.

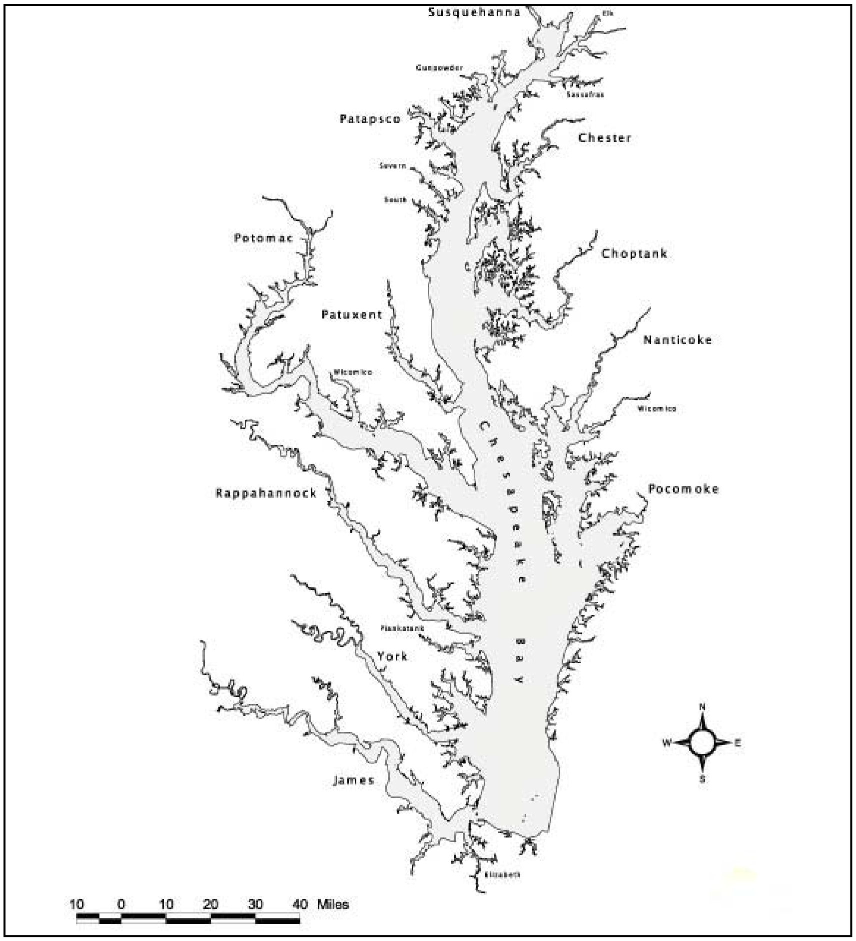

Figure 2.5. Chesapeake Bay and major tributaries.

3 Digital Elevation Model (DEM) Development

As a part of this larger work, the USACE Field Research Facility (FRF), RENCI, and ARCADIS developed a new and more detailed integrated topographic/bathymetric elevation Digital Elevation Model (DEM) of the Region III Study area. A topographic/bathymetric, or “Topo-Bathy” dataset is a merged terrestrial DEM and bathymetric (water depth) product. This product provides a single, integrated raster Geographic Information System (GIS) dataset that is useful for a variety of purposes, including inundation modeling, sea-level rise studies, and mapping. Development of the DEM (Figure 3.1) began on September 1, 2008 with data collection by USACE Philadelphia, Baltimore, and Norfolk Districts and the product was delivered in February 2010.

A 1/3 arc-second (~10 meter) elevation grid was generated from the best available digital datasets in the region. This section of the report provides a summary of the data sources and methodology used in developing the Region III DEM.

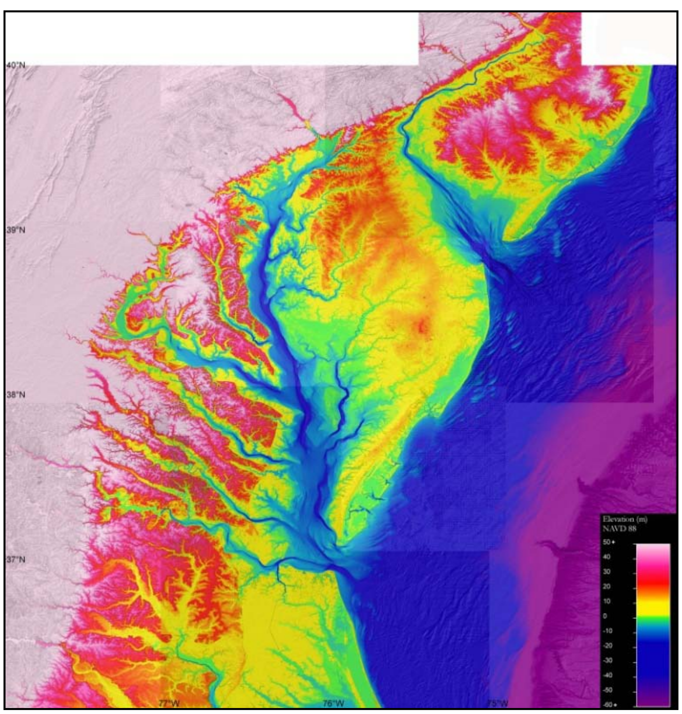

Figure 3.1. FEMA Region III DEM 10-meter raster topo-bathy dataset.

Figure 3.2 provides an illustration of the many different data sources, with varying spatial extents, used in the production in the DEM. (SHOWEX & Chesapeake/Delaware Bay ADCIRC Grid data coverage not included)

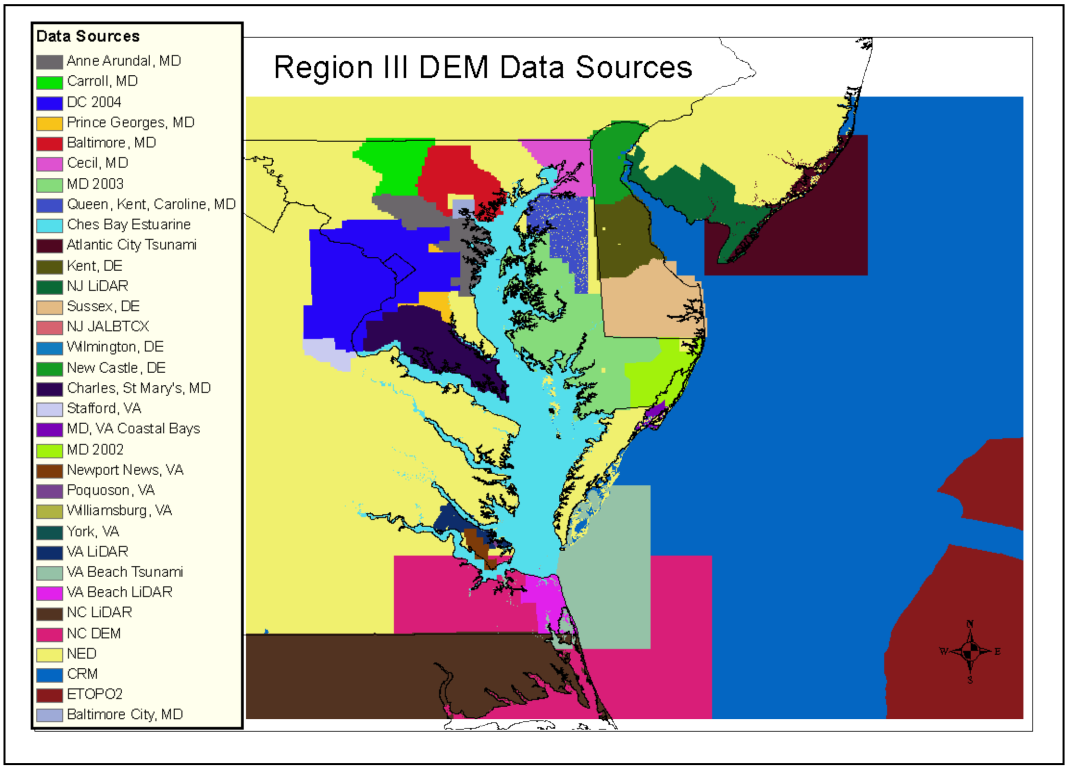

Figure 3.2. Region III DEM Data Sources.

Methodology

The integrated Region III coastal topo-bathy file was developed to meet the input requirements (Table 3.1) for the A Parallel Advanced Circulation Model for Oceanic, Coastal and Estuarine Waters (ADCIRC) model (Luettich et al. 1992). ADCIRC is a system of computer programs for solving time dependent, free surface circulation and transport problems in two and three dimensions (http://adcirc.org). The best available Topo-Bathy data were obtained by USACE personnel and RENCI and used to produce the final dataset. In particular, the USACE Philadelphia, Baltimore, and Norfolk district offices were instrumental in conducting a complete inventory of all available data sources for the region (Appendix A, Appendices A – G can be found on attached cd). Data sources, processing, re-projection, integration, and quality assessment are described in the following subsections.

Table 3.1. Specifications for FEMA Region III Grid.

Grid Area	Eastern and coastal North Carolina, Virginia, District of Columbia, Maryland, West Virginia, Delaware, Pennsylvania, and New Jersey: extending offshore approximately 73.00° to 78.00° W; 36.00° to 40.00° N, following the 15 meter contour inland and extending to the 50 meter bathymetric contour.
Coordinate System	Geographic decimal degrees
Horizontal Datum	NAD83
Vertical Datum	NAVD88
Vertical Units	Meters
Grid Spacing	1/3 arc-seconds (~10 meters)
Grid Format	ASCII raster grid

Data Sources and Processing

Topographic and bathymetric data were obtained from numerous sources, including: the U.S. Geological Survey (USGS) National Elevation Data (NED); the NOAA National Ocean Service (NOS), Office of Coast Survey (OCS), and National Geophysical Data Center (NGDC); the U.S. Army Corps of Engineers (USACE); the individual states; and the North Carolina Division of Emergency Management - Floodplain Mapping Program (NCDEM-FPMP). Appendix A provides specific information regarding the source, use, and manipulation of each dataset used in the DEM. Figures 3.3 through 3.5 provide graphical overviews of the bathymetric datasets, the topographic datasets, and a close up of the datasets as seen in the Prince Georges County, MD region.

The Geographic Resources Analysis Support System (GRASS) v. 6.3 (http://grass.itc.it/), ESRI ArcGIS v. 9.3 (http://www.esri.com/), VDatum (http://nauticalcharts.noaa.gov/csdl/vdatum.htm), Fledermaus (http://www.ivs3d.com/-products/fledermaus/) and Golden Software Surfer http://www.goldensoftware.com/-products/surfer/surfer.shtml were used to process, analyze, display, and interpolate data, as well as to conduct quality assessment. Datasets were converted and transformed to NAVD88 and NAD83 geographic coordinates using GRASS and ArcGIS. Vertical datum transformations were achieved using VDatum model software that was developed jointly by OCS and NOAA's National Geodetic Survey.

Table 3.2. Datasets and Percentage of Use in Version 2.0 of the DEM.

Dataset	Percentage
VA LiDAR	1.22%
NJ LiDAR	1.3%
DE LiDAR	3.45%
MD LiDAR	9.87%
DC	3.38
Atlantic City Tsunami	3.24%
Virginia Beach Tsunami	3.28%
NCFMP LiDAR	6.36%
NC DEM version 2.6	6.37
NED	29.3%
CRM	20.86%
ETOPO2v2	5.23%
Chesapeake Bay Estuarine & MDVA Coastal Bays	6.14%

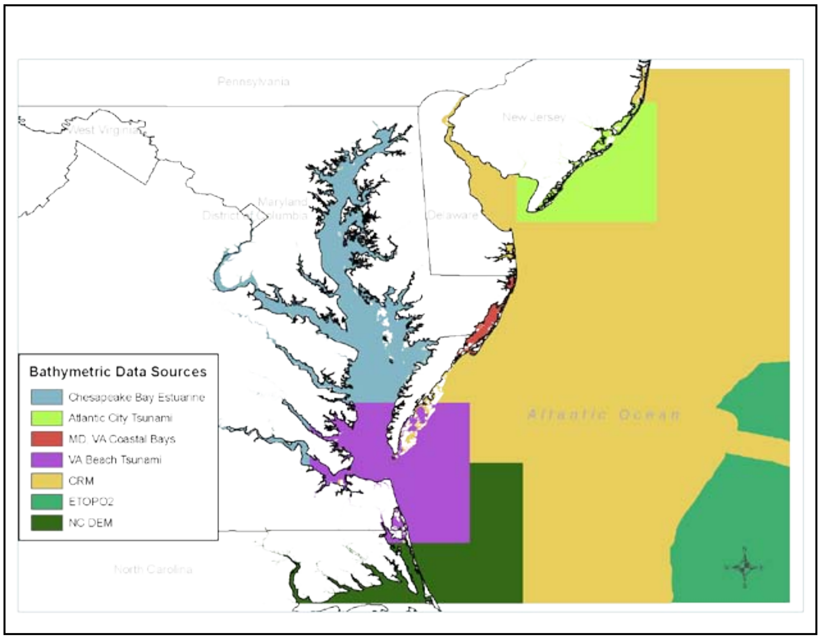

Figure 3.3. Region III DEM Bathymetric Data Sources (Does not show SHOWEX or Chesapeake/Delaware Bay ADCIRC Grid data coverage).

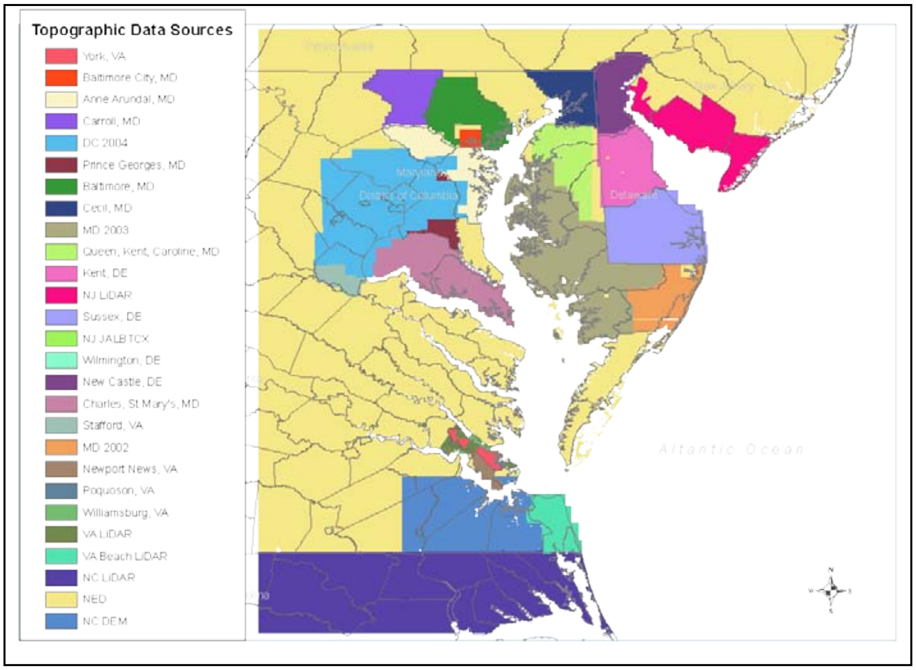

Figure 3.4. Region III DEM Topographic Data Sets.

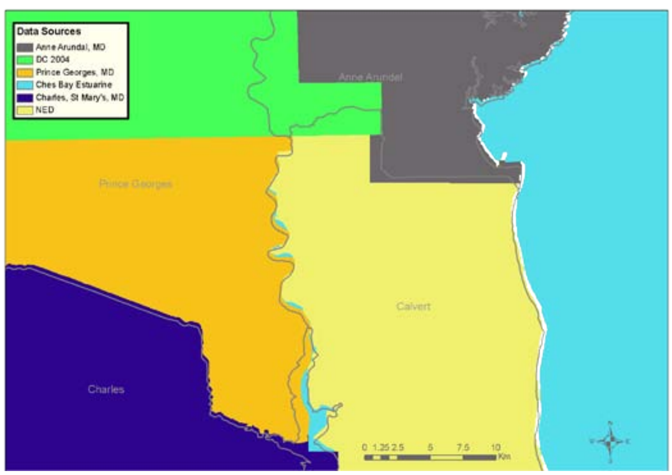

Figure 3.5 Region III DEM Data Sets.

Data Sources

The relative amount of data from each of the individual sources for the entire dataset is shown in Table 3.2. More information regarding sources and manipulation can be found in Appendix A.

Data Organization

As a result of the size of the study area, the number of US states involved in the study, and the sheer number of datasets, an organization process

Table 3.3. TEC Datasets Used in the Development of the DEM.

City (Year)	Format	Original Vertical Datum	Original Horizontal Datum
Washington, DC	GRID	NAVD88	WGS84, UTM18
Baltimore County, MD	TIF	NAVD88	WGS84, UTM18
Newport News, VA	TIF	NAVD88	VA State Plane NAD83 HARN
Virginia Beach, VA	TIF	NAVD88	WGS84, UTM18
Williamsburg and Yorktown, VA	TIF	MSL	WGS84, UTM18
York, VA	TIF	MSL	WGS84, UTM18
Poquoson, VA	TIF	MSL	WGS84, UTM18
Note: More detailed information regarding these datasets can be found in Appendix A.			

was required for the DEM development process. Twenty one 1 degree overlapping tiles were identified and used for the clipping process. The overlap was defined so that data would not be lost in the clipping process. Figure 3.6 illustrates the distribution of the graticule tiles.

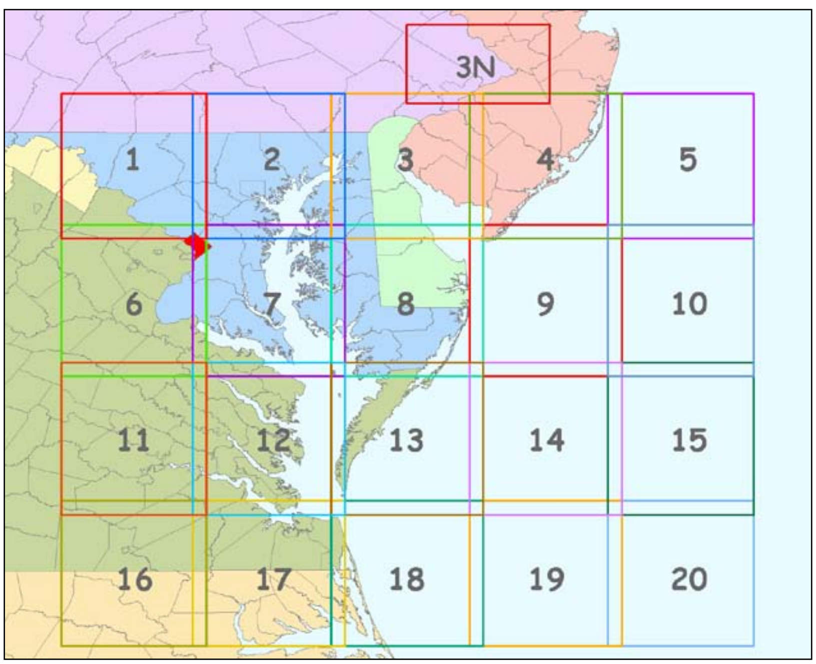

Figure 3.6. Data Organization Graticule.

Bathymetry

Bathymetric datasets used in the compilation of the Region III DEM include: Chesapeake/Delaware Bay ADCIRC Grid; Coastal Relief Model

(CRM) data; SHOaling Waves Experiment (SHOWEX) data; Chesapeake Bay Bathymetry; Maryland and Virginia Coastal Bays Bathymetry; and NOAA ETOPO2v2 satellite radar data. The datasets varied widely in terms of cell resolution, data sources, and publication date. They also had varied map projections and vertical and horizontal datums. The collection, conversion, and preparation of each of the datasets used in creation of the bathymetry of version 1.0 of the DEM are described below. Once compiled in a form, the complete collection of bathymetry data was interpolated using the software Fledermaus. Figure 3.7 illustrates the bathymetry data used for this project (and described below).

Figure 3.7 Region III DEM Bathymetry.

Bathymetry data was also used to mask out inaccurate elevations in topographic data located near/in water features. These inaccuracies were artifacts of the data processing used to create the LiDAR-derived DEM, and were removed as a part of the data manipulation to create a seamless topo-bathy dataset

The Chesapeake/Delaware Bay ADCIRC Grid

The Chesapeake/Delaware Bay ADCIRC Grid was developed by NOAA to define the conversion areas for VDatum. VDatum is used to convert between tidal and orthometric datums and is often used for inundation modeling.

The data were originally provided by NOAA in a model zero vertical datum. Upon request, it was provided a second time referenced to MSL. The extent of the dataset can be seen in Figure 3.8. VDatum polygons were used to separate the data points into the appropriate VDatum conversion areas. VDatum was then used to convert the vertical datum from MSL to NAVD88. The resulting datasets were cleaned of any null values and converted from a tab delimited format to a comma delimited text file using a Perl script.

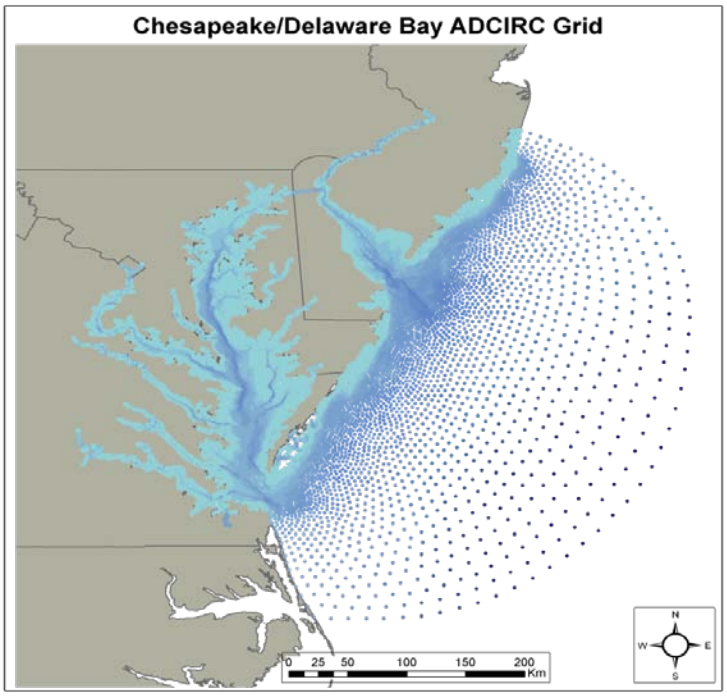

Figure 3.8 NOAA ADCIRC Grid.

SHOaling Waves Experiment (SHOWEX) Data

USACE gathered SHOWEX data in 1999 as part of an experiment designed to "improve the scientific understanding of the properties and evolution of surface gravity waves in intermediate and shallow water depths (typical of inner continental shelves up to the edge of the surf zone)" (Graber 2009).

The data was provided by USACE referenced to the horizontal datum NAD83 and the vertical datum MLW. The extent of the dataset can be seen in Figure 3.9. VDatum polygons were used to separate the data points into the appropriate VDatum conversion areas. VDatum was then used to convert the vertical datum from MLW to NAVD88. The resulting datasets were cleaned of any null values and converted from a tab-delimited format to a comma delimited text file using a Perl script.

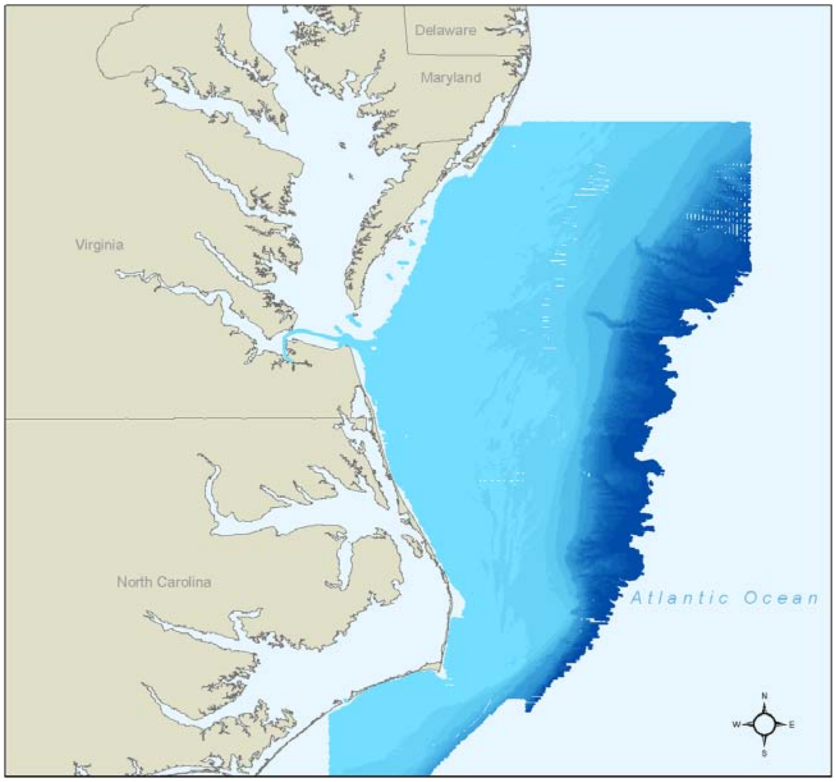

Figure 3.9 Shoaling Waves Experiment Data.

NOAA Tsunami datasets

Prior to the start of this project, the NOAA Pacific Marine Environmental Laboratory, center for Tsunami Inundation Mapping Efforts (TIME) project completed detailed topo-bathy datasets for the Virginia Beach and Atlantic City (Taylor et al. 2007 and 2008) (http://www.ngdc.noaa.gov/mgg/inundation/). The extents of the combined bathymetric-topographic DEMs data are shown in Figure 3.10.

The data have a cell size of 1/3 arc-seconds (~10 meters), and are compilations of multiple datasets of varying sources and detail. Both datasets were created using similar approaches and the best available data. Individual bathymetric datasets used in the compilation of the DEM included multiple NOS hydrographic surveys, OCS electronic nautical charts, LiDAR survey, and deep-water multibeam surveys of the U.S. Atlantic margin conducted by the Center for Coastal and Ocean Mapping/Joint Hydrographic Center (CCOM/JHC).

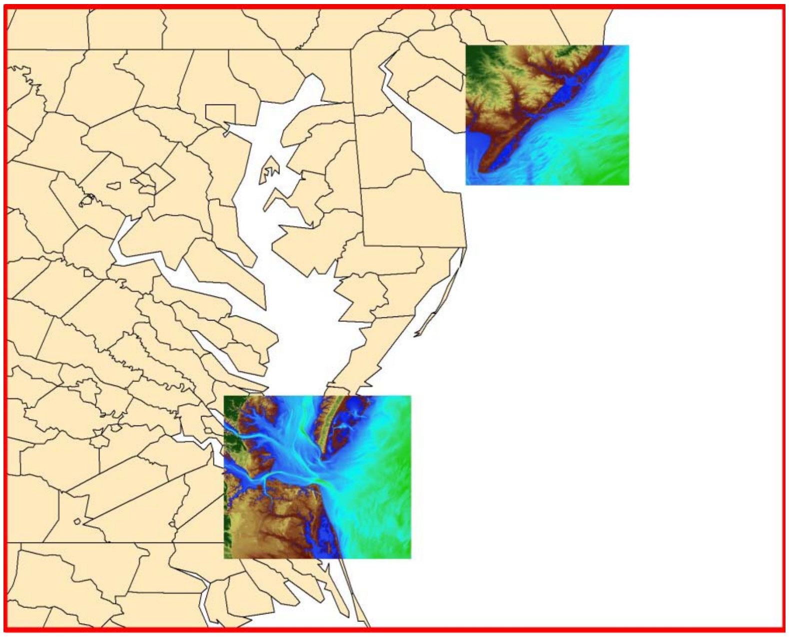

Figure 3.10. Atlantic City and Virginia Beach Tsunami Dataset Distribution.

The topo-bathy datasets were obtained via Internet download and originally vertically referenced to Mean High Water and horizontally referenced to geographic coordinates (WGS 84). The datasets were separated into “land data” and “water data” using ArcGIS’s raster calculator functions:

Tsunami_land = setnull(<raster_dataset> < 0, <raster_dataset>)

Tsunami_water = setnull(<raster_dataset> >= 0, <raster_dataset>)

The Tsunami datasets are categorized as Bathymetric only datasets for this project. Topographic data alignment discrepancies were observed in some areas when comparing the Tsunami interpolated dataset with actual LiDAR data. In addition, modern high resolution data was available for many areas that were not included in the Tsunami datasets assembled in 2007. VDatum polygons were used to separate the water data points into the appropriate VDatum conversion areas. VDatum was then used to convert the vertical datum from MHW to NAVD88. The resulting datasets were cleaned of any null values and converted from a tab delimited format to a comma delimited text file using a Perl script. Horizontal datum conversion was achieved using ArcGIS to convert from WGS84 to NAD83.

Chesapeake Bay Bathymetry and MD & VA Coastal Bays Bathymetry Datasets

The Chesapeake Bay Bathymetry dataset was downloaded from NOAA's Estuarine Bathymetry website in the form of three GRID files. The files were referenced to a horizontal datum of UTM18, NAD27 and a vertical datum of MLLW. Each GRID file was imported into GRASS in a UTM18, NAD27 project area and reprojected to geographic coordinates, NAD83 using GRASS' r.proj function, a utility for re-projecting spatial data. Three separate XYZ text files were exported using r.stats a GRASS utility for writing out point information. VDatum was used to convert the vertical datum from MLLW meters to NAVD88 meters using the predefined VDatum project areas.

The Maryland and Virginia Bay Bathymetry datasets were downloaded from Maryland Geological Survey website in the form of two GRID files. The files were referenced to a horizontal datum of UTM18, NAD83 and a vertical datum of NAVD88. The Maryland dataset was referenced to meters and the Virginia dataset was referenced to centimeters. Each GRID file was imported into GRASS in a UTM18, NAD83 project area and reprojected to geographic coordinates, NAD83 using GRASS' r.proj function. Two XYZ text files were exported using r.stats. The vertical units for the Virginia dataset were converted from centimeters to meters using a Perl script. Figure 3.11 illustrates the geographic extent of the Chesapeake Bay, Maryland, and Virginia Bathymetry datasets.

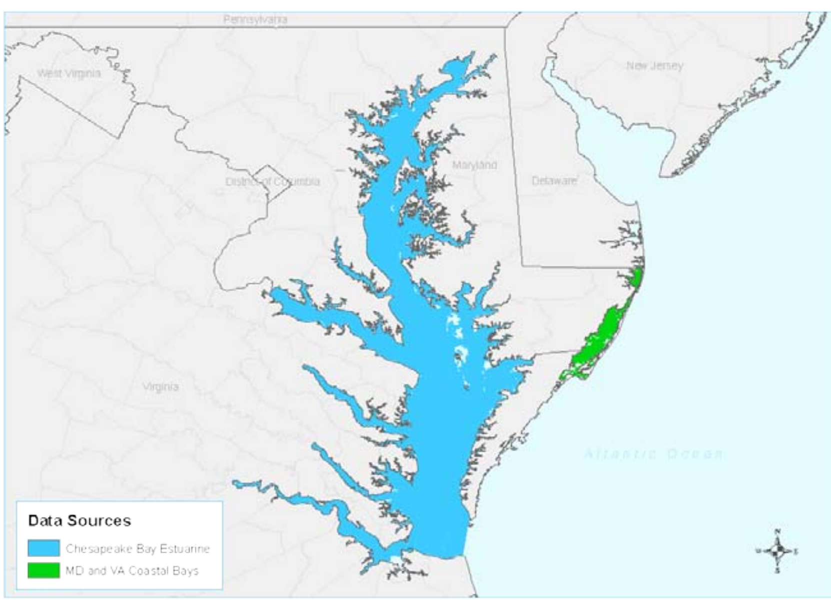

Figure 3.11 Chesapeake Bay Estuarine and MD, VA Coastal Bays data extents.

NOAA ETOPO2v2

Portions of the study area farther offshore, including outside the coastal shelf, were not available in other datasets. This area was represented using the NOAA ETOPO2v2 data (US Department of Commerce 2006). The ETOPO2v2 data used in the development of the DEM are displayed in Figure 3.12. The primary source of the data for this area is the "Smith & Sandwell" database. This is a worldwide set of 2-minute gridded ocean bathymetry derived from 1978 satellite radar altimetry of the sea surface. The horizontal datum is WGS-84 and the vertical datum is Mean Sea Level (NOAA NGDC 2008). The horizontal grid spacing was 2-minutes of latitude and longitude (1 minute of latitude = 1.853 km at the Equator). The vertical precision was 1 meter. The projection was the Cylindrical Equidistant (Plate Carrée), or geographic projection. The data was obtained via Internet download and included in the offshore interpolation process. A vertical conversion was not performed since the difference between MSL and NAVD88 is unknown at this remote location. In addition the depths comprising this dataset (>1000m) will have little to no effect on the model.

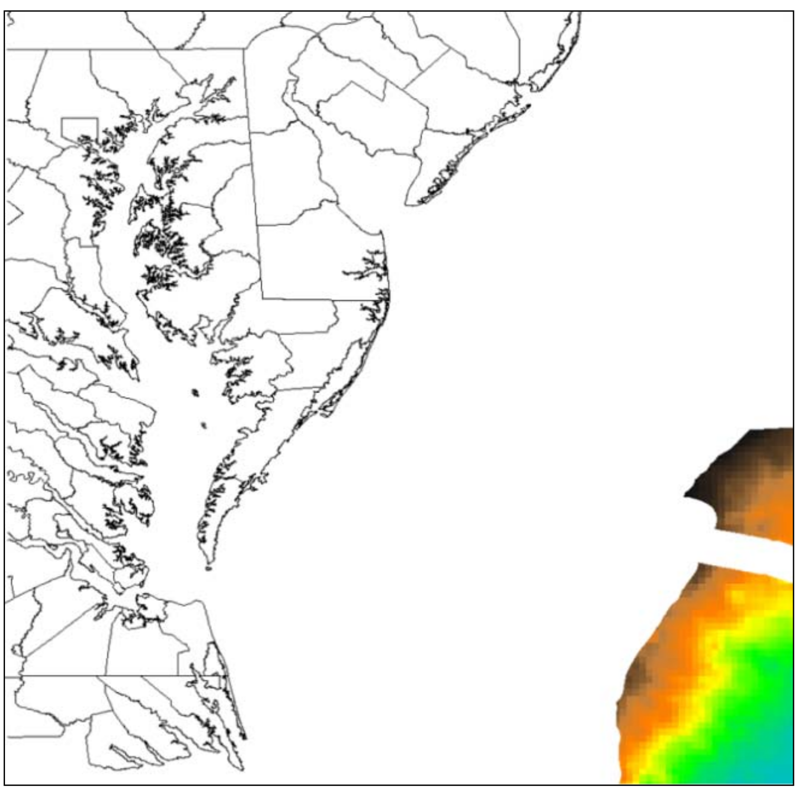

Figure 3.12 ETOPO2 Bathymetric Data.

U.S. Army Corps of Engineers Delaware River Transects & the Addition of Tile 3 North

The USACE Philadelphia District provided Delaware River Cross-Section data shown in Figure 3.13 that extended North up the Delaware River to well above Trenton, NJ, the approximate point where tidal influences change to fluvial. These data were referenced to NAD83 NJ State Plane and NAVD88 with units of feet and then re-projected using the USACE program Corpscon to geographic coordinates and vertical units to meters. These bathymetric data coupled with the NED topographic data were critical in the addition of Tile 3 North shown in Figure 3.14.

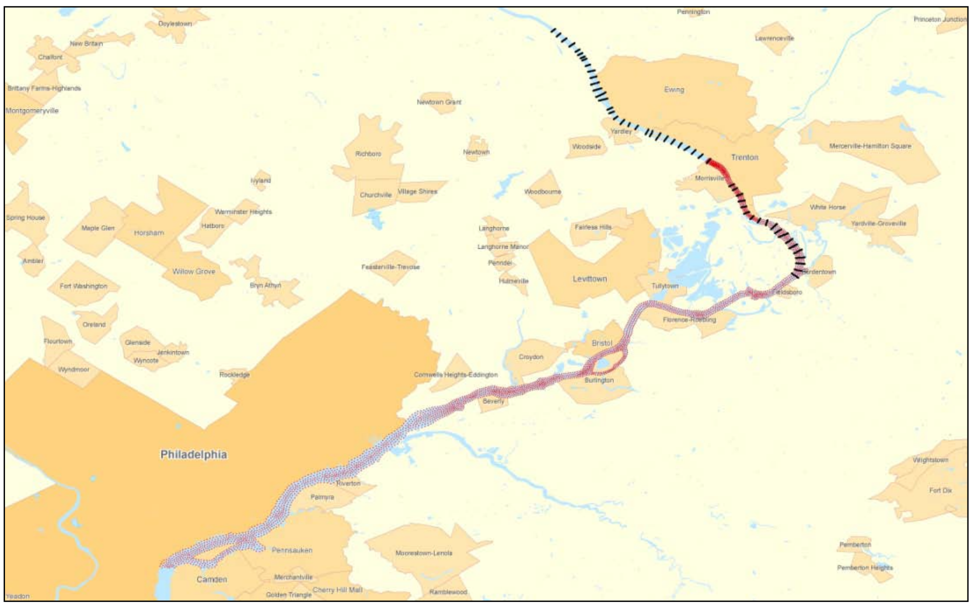

Figure 3.13 USACE Delaware River Cross-Sections Black lines show spatial coverage of USACE Data.

Topography/Bathymetry Data

Merged topographic-bathymetric data sets consist of elevation measurements that cross the subaerial-submarine coastal transition zone. The datasets are often collected or assembled with the objective of accurately resolving the shoreline interface for use in storm damage or inundation analyses.

The NOAA Coastal Relief Model (CRM)

The Coastal Relief Gridded database (http://www.ngdc.noaa.gov/mgg/coastal/coastal.html) provides a comprehensive view of the US Coastal Zone extending from the coastal state boundaries to as far offshore as the NOS hydrographic data will support a continuous view of the seafloor (Divins and Metzger 2007). The CRM dataset was used in the FEMA Region III DEM.

Bathymetric data sources for the CRM dataset include the NOS Hydrographic Database (http://www.ngdc.noaa.gov/mgg/bathymetry/hydro.html), the USGS, the USACE LiDAR (CHARTS), and various academic institutions.

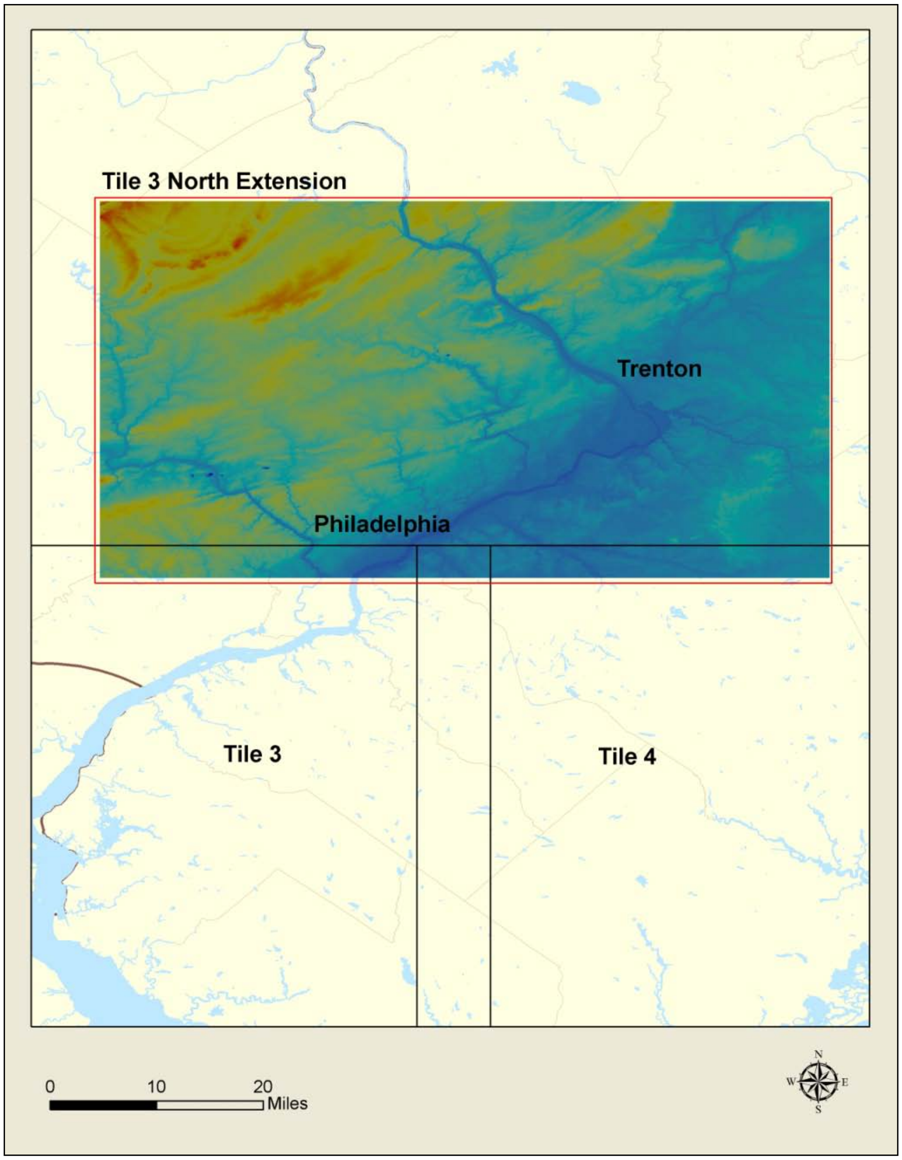

Figure 3.14 Tile 3 North Extension enclosed in red rectangle above.

Topographic data are from the USGS 3-arc-second DEMs and Shuttle Radar Topography Mission (SRTM) data. The data provide a consistent dataset of the US coastal zone. The database is assembled by gridding the NOS sounding data at the same 3 arc-second (~90 meters) resolution and registration as the USGS 3-arc-second DEMs and splicing the two data sets at the NOS medium-resolution vector shoreline (http://seaserver.nos.noaa.gov/-projects/shoreline/shoreline.html). The principal component of the database is 3-arc-second elevation grids of areas 1° in longitude by 1° in latitude, in which elevations are resolved to 1/10 of a meter.

The data was obtained via Internet download and vertically corrected as a series of ASCII grids. The CRM bathymetric data are referenced to their original datum (MLW, MLLW, or LWD). Since approximately 90% of the bathymetric data in the database are referenced to MLW, the data were corrected to NAVD88 using the MLW to NAVD88 datum corrections using VDatum. Figure 3.15 represents the Coastal Relief Model data extracted for this study.

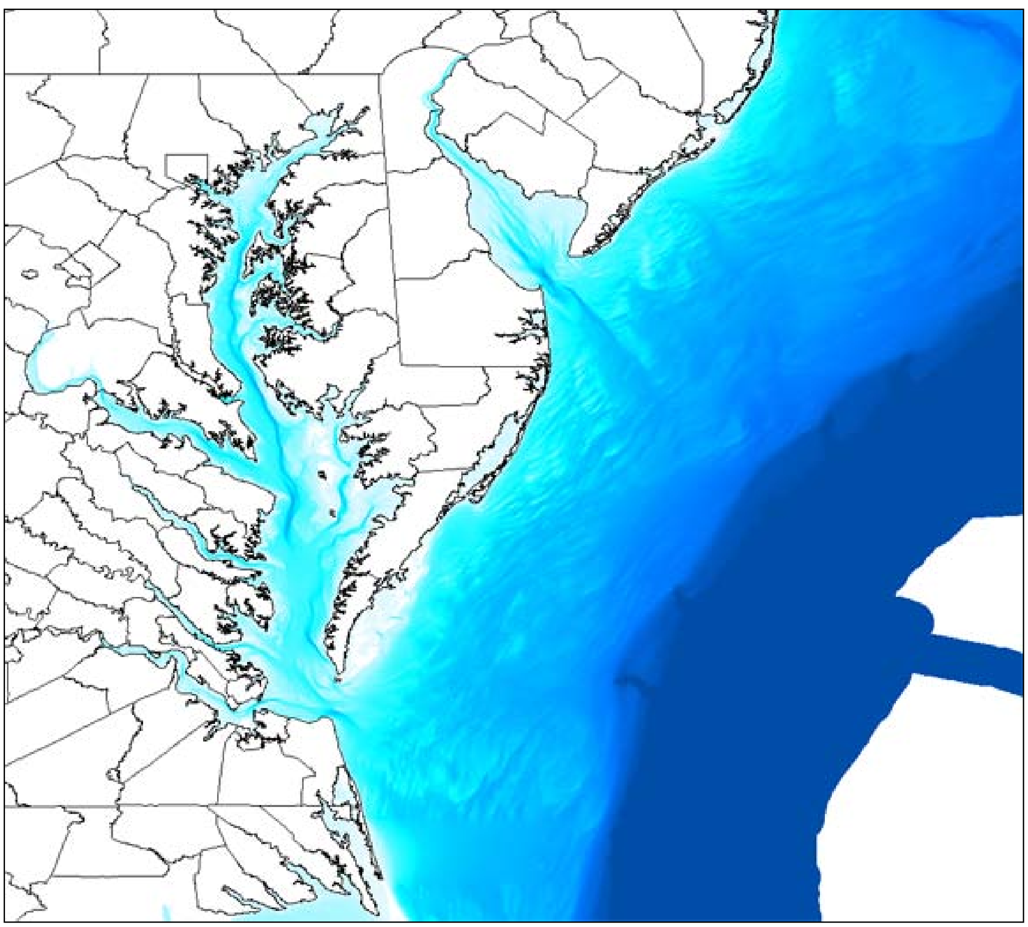

Figure 3.15 Coastal Relief Model Data.

Topographic Data

Several topographic datasets were available for the study area. These data varied widely in terms of resolution, data sources, and publication date. They also had varied map projections and vertical and horizontal datums. Each of the datasets used in creation of the DEM is described below in a data table and Appendix F describes the data attributes in more detail.

Topographic Engineering Center Datasets (predominantly Virginia Datasets)

Multiple datasets provided by (TEC) were used in the development of the DEM and are listed in Table 3.3. In particular, many of the datasets discussed below cover the Commonwealth of Virginia. Two datasets are an exception – the Washington, DC dataset covered the District of Columbia, portions of Northern Virginia, and select counties in Maryland. Additionally, the TEC provided Baltimore County data that was used in the DEM. The processes used to reproject and export the selected TEC datasets are discussed below.

The data were obtained via hard drive delivery from TEC. Multiple data formats were received and evaluated. Datasets that did not represent bare earth conditions or were incomplete via a lack of complete data or metadata were eliminated. The selected datasets were imported into GRASS and reprojected to a horizontal datum of geographic coordinates, NAD83. The GRASS r.stats function was used to export an XYZ text file, which was used in the DEM interpolation process. Figure 3.16 represents the geographic distribution of these datasets.

New Jersey Datasets

New Jersey forms the northern portion of the DEM and is actually outside the Region III study area. It was determined that adjacent areas may impact surge in the study area. Therefore, a number of datasets were evaluated for the state of New Jersey. The majority of the datasets were derived from CRM or NED already included in the DEM. The Cape May, Cumberland, and Salem Counties dataset was used to provide greater detail than the other existing data provided.

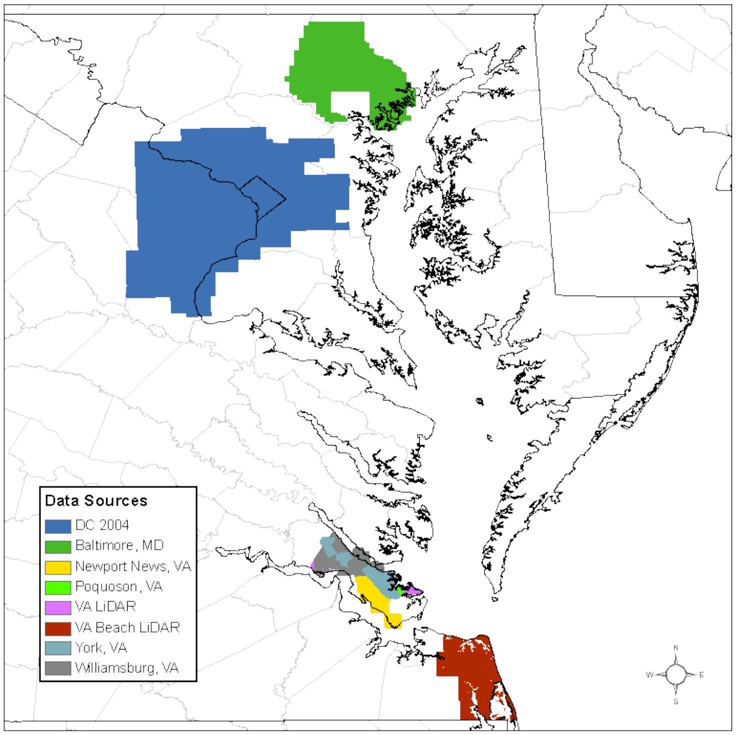

Figure 3.16 TEC Data Extents.

Cape May, Cumberland, and Salem Counties, NJ

The Cape May, Cumberland, and Salem Counties, NJ datasets were provided by USACE in the form of three Arc binary raster files. The files were referenced to New Jersey State Plane horizontal datum and NAVD88 meters vertical datum. Each raster file was imported into GRASS in a New Jersey State Plane project area and re-projected to geographic coordinates, NAD83 using GRASS' r.proj function. The datasets were combined with GRASS' r.patch function and then one XYZ text file was exporting using r.stats. Figure 3.17 illustrates the spatial extent of the dataset.

Delaware Datasets

LiDAR data from New Castle, Sussex, and Kent Counties in Delaware were used in the development of the DEM. All datasets were provided in a horizontal datum of Delaware State Plane and a vertical datum of NAVD88, Meters. Figure 3.18 illustrates the spatial extent of the New Castle, Kent and Sussex County datasets.

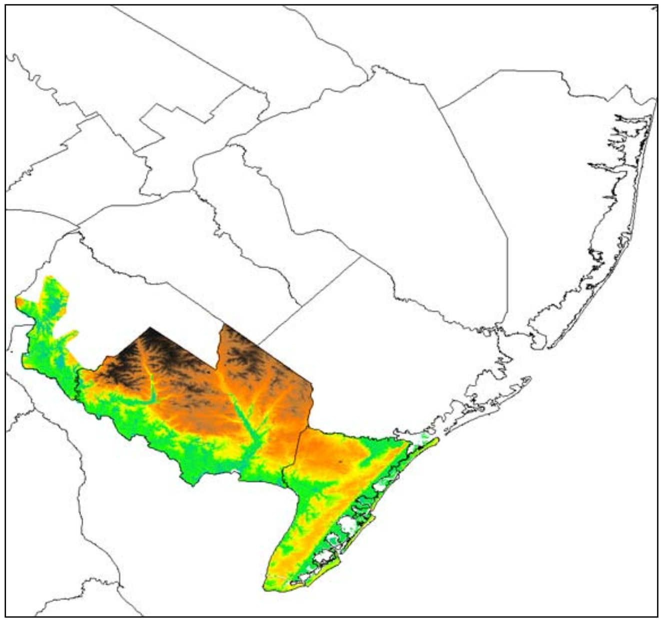

Figure 3.17 Southern NJ LiDAR Datasets.

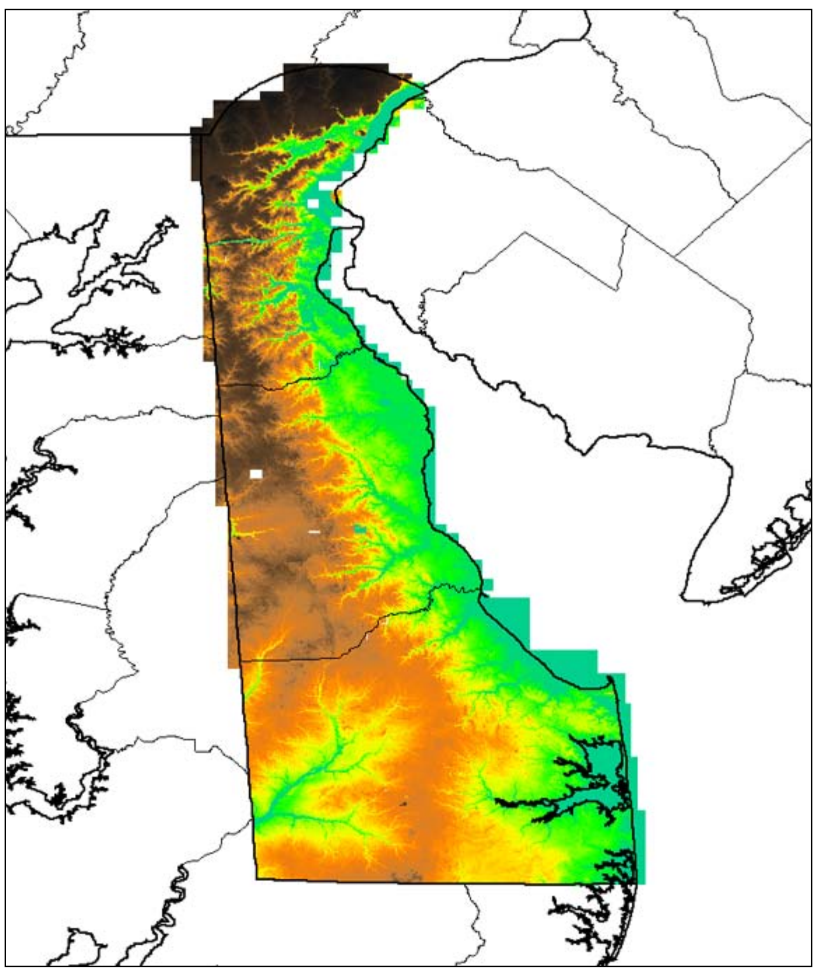

Figure 3.18 Delaware: New Castle, Kent and Sussex LiDAR Data.

Kent County, DE

Kent County, DE was provided in GRID format consisting of 598 files. ARCADIS processed the data by utilizing an ArcGIS batch mode to define the original data projection. A second batch process was used to re-project the horizontal datum to geographic coordinates, NAD83. The GRID was then converted to a point feature class and the X and Y attribute fields were added. A Z field was added and calculated and the feature class was exported to a table. This process was repeated for all 598 tiles and then all tables were converted into one table, which was then exported to an ASCII file.

Sussex County, DE

Sussex County, DE was provided by USACE as one GRID file. ArcGIS was used to re-project the horizontal datum to geographic coordinates, NAD83. An ArcGIS script, Raster2XYZ, was used to export the reprojected GRID to an XYZ text file. This data contained false elevation values over areas where the dataset met the Delaware Bay bathymetric data. A perl script was used remove all elevation values less than 0 meters.

Maryland Datasets

USACE provided a number of datasets for Maryland counties. Duplicate datasets were often provided in multiple formats (e.g., .txt, GRID, etc.). All datasets were evaluated and the datasets discussed here were determined to represent bare earth data and were complete.

Baltimore City, MD

Baltimore City LiDAR data was provided as four TIF files referenced to WGS84, UTM18 horizontal datum and a NAVD88 vertical datum in meters. The data was imported into GRASS in a UTM18 project area and re-projected to geographic coordinates, NAD83 using The GRASS r.proj function. The resulting dataset was exported to an XYZ text file using the r.stats function. Figure 3.19 illustrates the spatial extent of the Baltimore City dataset.

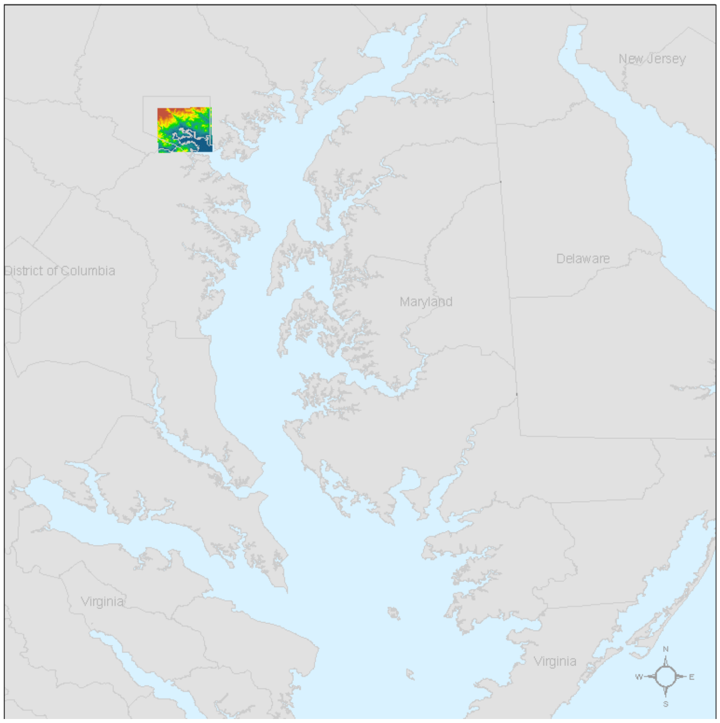

Figure 3.19. Baltimore City, MD LiDAR Data.

Baltimore County, MD

Baltimore County LiDAR data was provided in GRID format referenced to a Maryland State Plane, NAD83 horizontal datum and a NAVD88 vertical datum in feet. The data was imported into GRASS in a Baltimore County project area and re-projected to geographic coordinates, NAD83 using GRASS' r.proj function. The resulting dataset was exported to an XYZ text file using the r.stats function and a Perl script was used to convert the vertical coordinates from feet to meters. Figure 3.20 illustrates the spatial extent of the Baltimore County dataset.

Carroll County, MD

Carroll County LiDAR data was provided in GRID and Geodatabase format referenced to Maryland State Plane, NAD83 horizontal datum and a NAVD88 vertical datum in feet. The data was reprojected to geographic coordinates, NAD83 using the ArcGIS Project function. The resulting dataset was imported into GRASS and exported to an XYZ text file using the r.stats function. A Perl script was then used to convert the vertical coordinates from feet to meters. Figure 3.21 illustrates the spatial extent of the Carroll County dataset.

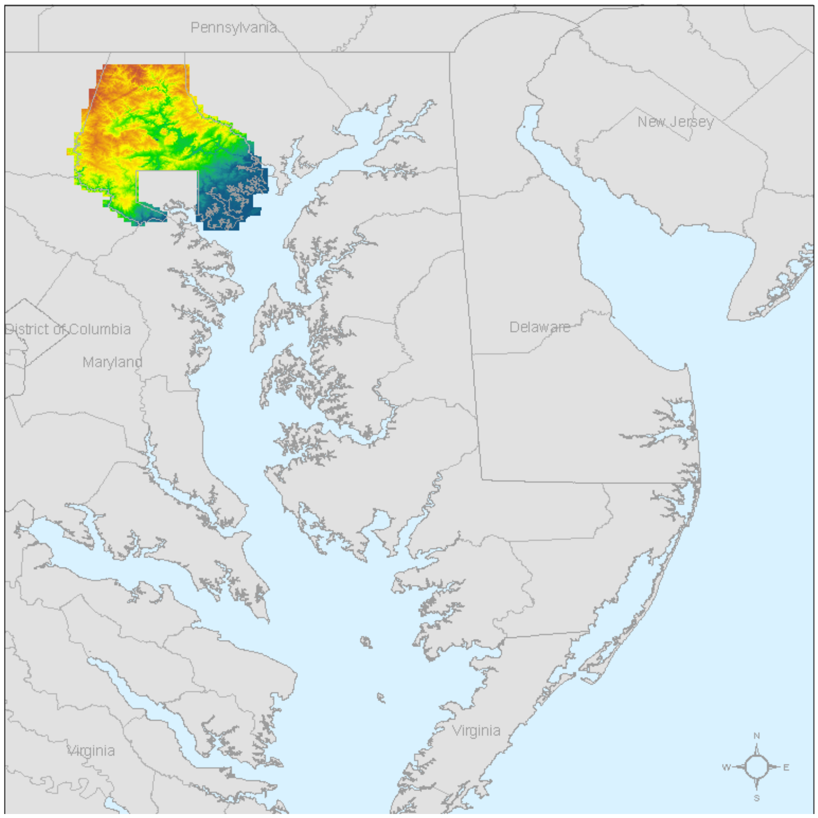

Figure 3.20. Baltimore County, MD LiDAR Data.

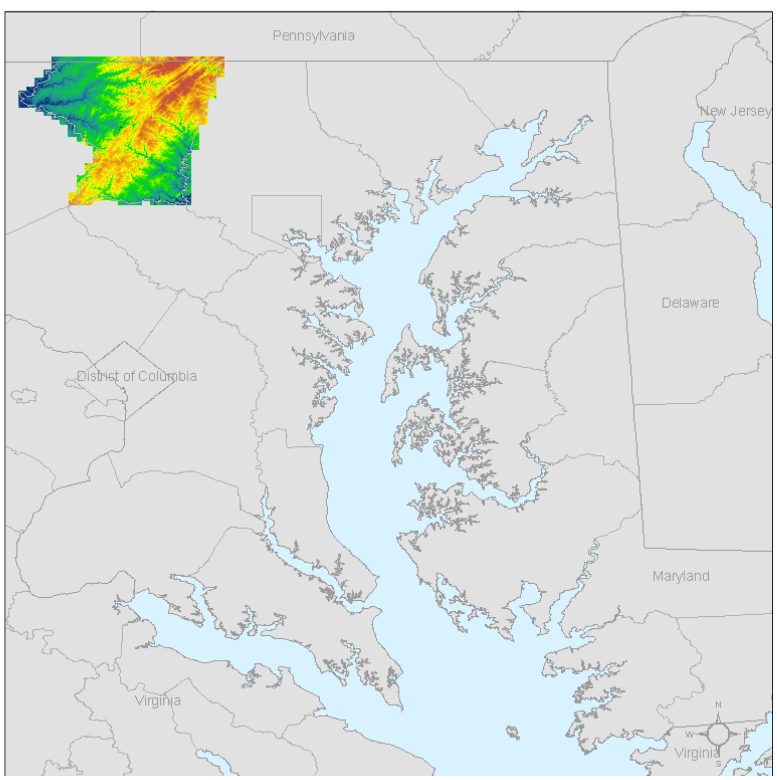

Figure 3.21. Carroll County, MD LiDAR Data.

Cecil County, MD

Cecil County LiDAR data was provided in GRID format referenced to a Maryland State Plane, NAD83 horizontal datum and a NAVD88 vertical datum in feet. The data was imported into GRASS in a Cecil County project area and re-projected to geographic coordinates, NAD83 using the GRASS r.proj function. The resulting dataset was exported to an XYZ text file using the r.stats function and a Perl script was used to convert the vertical coordinates from feet to meters. Figure 3.22 illustrates the spatial extent of the Cecil County dataset.

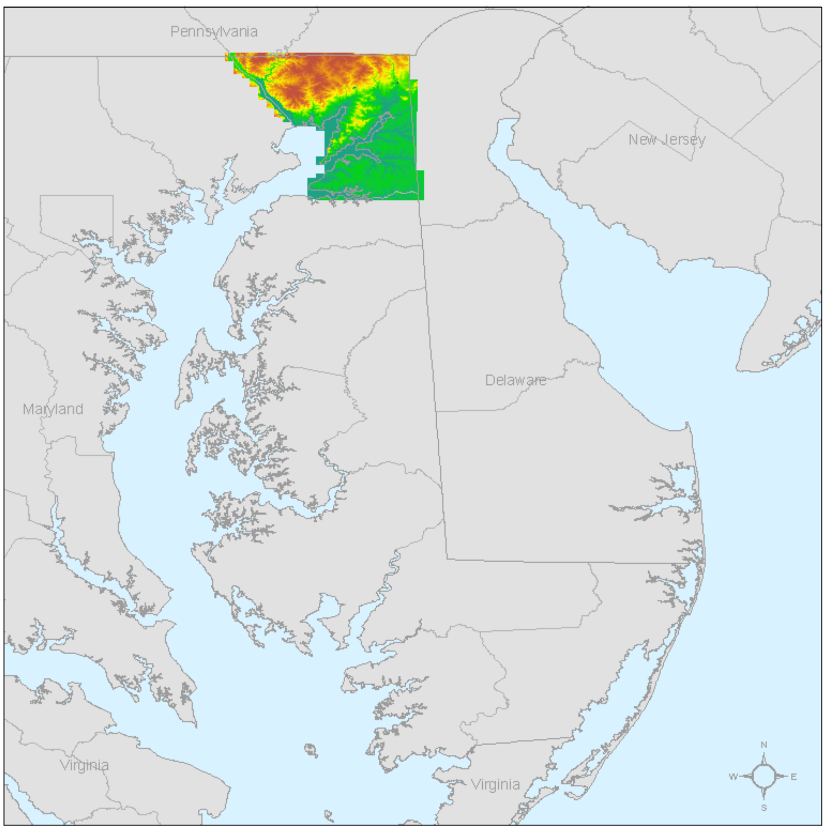

Figure 3.22. Cecil County, MD LiDAR Data.

Dorchester, Somerset, Talbot, Wicomico Counties, MD with portions of Caroline, Kent, and Queen Anne Counties

A Maryland LiDAR dataset collected in 2003 was provided by USACE. This dataset was divided into east and west folders and covered Dorchester, Somerset, Talbot, and Wicomico counties. The dataset also covered portions of Caroline, Kent, and Queen Anne Counties in Maryland. The data was provided in the form of 899 GRID files. ARCADIS processed the data by utilizing an ArcGIS batch mode to define the original data projection. A second batch process was used to reproject the horizontal datum to geographic coordinates, NAD83. The GRID was then converted to a point feature class and the X and Y attribute fields were added. A Z field was added and calculated and the feature class was exported to a table. This process was repeated for all 899 tiles and then all tables were converted into tables, which were then exported to ASCII files. Figure 3.23 illustrates the spatial extent of the dataset.

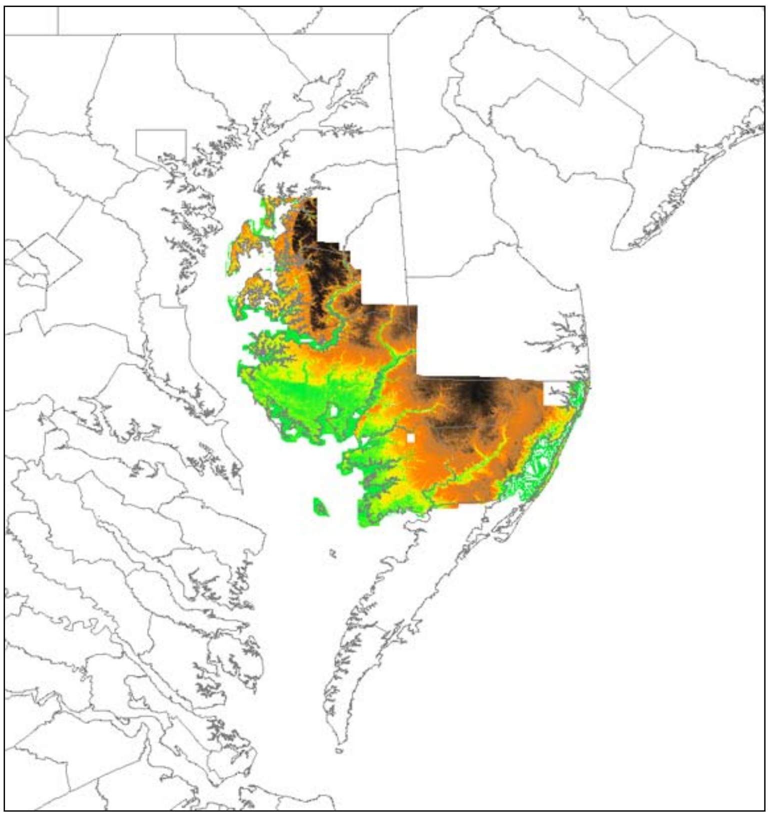

Figure 3.23. Dorchester, Somerset, Talbot, Wicomico Counties , MD LiDAR Data.

Kent, Queen Anne's, Caroline Counties, MD

LiDAR data for Kent, Queen Anne’s, and Caroline Counties in Maryland were provided by USACE in the form of 45 FLT files. ArcGIS was used to convert the FLT files to raster files. All files were then imported into GRASS and patched together into one raster file using the GRASS r.patch function. An XYZ text file was exported using GRASS’ r.stats function. Finally, vertical units were converted from MLLW/meters to NAVD88/meters using VDatum. Figure 3.24 illustrates the spatial extent of the dataset.

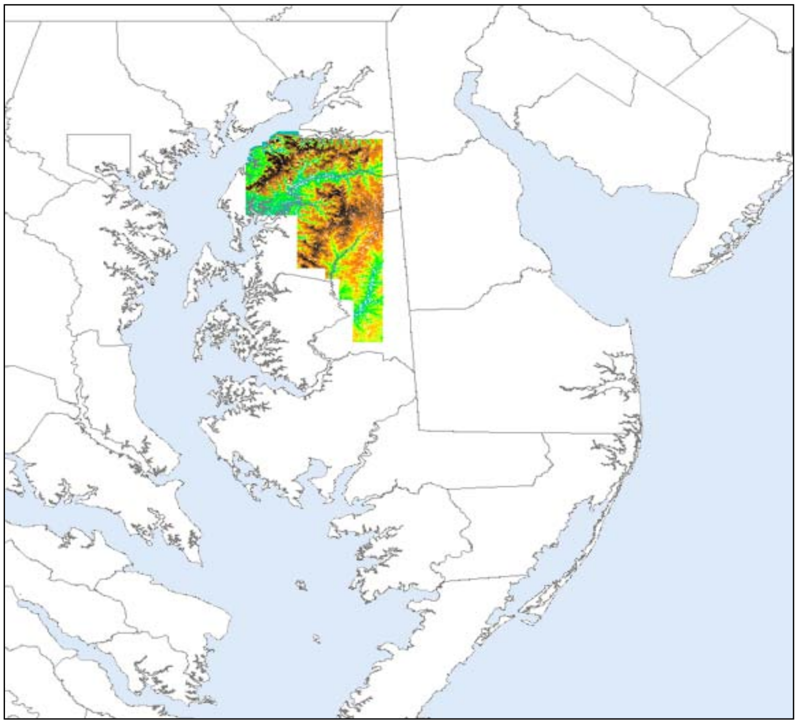

Figure 3.24. Queen, Kent, Caroline Counties, MD LiDAR.

Prince George's County, MD

Prince George's County data was provided in GRID format referenced to Maryland State Plane, NAD83 horizontal datum and NAVD88, feet vertical datum. The GRID file was reprojected in ArcGIS using the Project function to geographic coordinates, NAD83. An XYZ text file was exported using the ArcGIS Raster2XYZ script. A Perl script was used to convert the vertical coordinates from feet to meters. Figure 3.25 illustrates the spatial extent of the Prince George's County dataset.

Worchester County, MD

A LiDAR dataset collected in Worchester County, Maryland in 2002 was provided by USACE. The data was provided in the form of 28 GRID files. ARCADIS processed the data by utilizing an ArcGIS batch mode to define the original data projection. A second batch process was used to reproject the horizontal datum to geographic coordinates, NAD83. The GRID was then converted to a point feature class and the X and Y attribute fields were added. A Z field was added and calculated and the feature class was exported to a table. This process was repeated for all 28 tiles and then all fields were converted into tables, which were then export to ASCII files. Figure 3.26 illustrates the spatial extent of the Worchester County dataset.

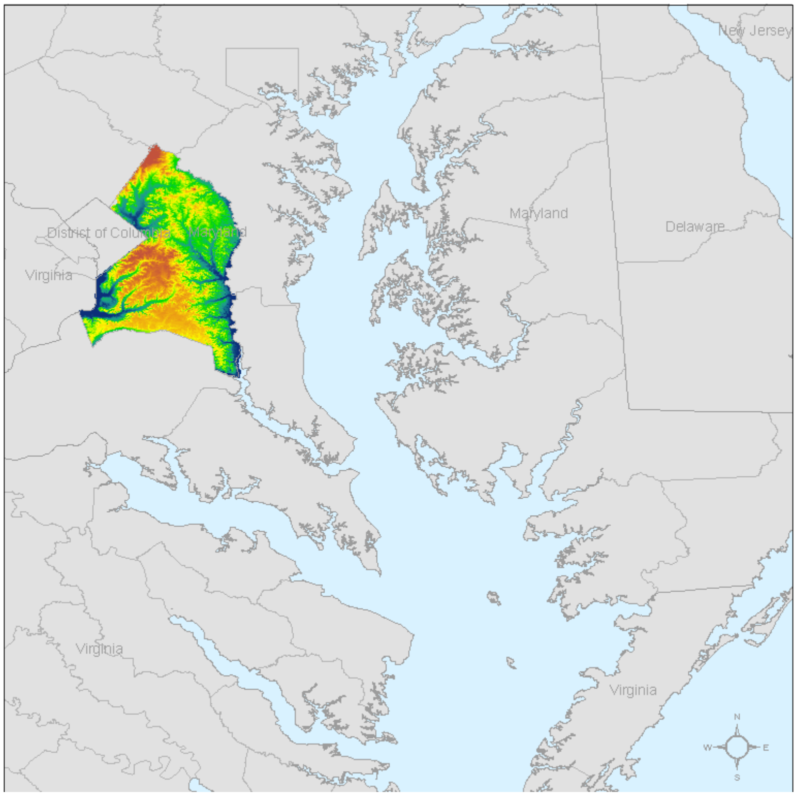

Figure 3.25. Prince Georges County, MD LiDAR Dataset.

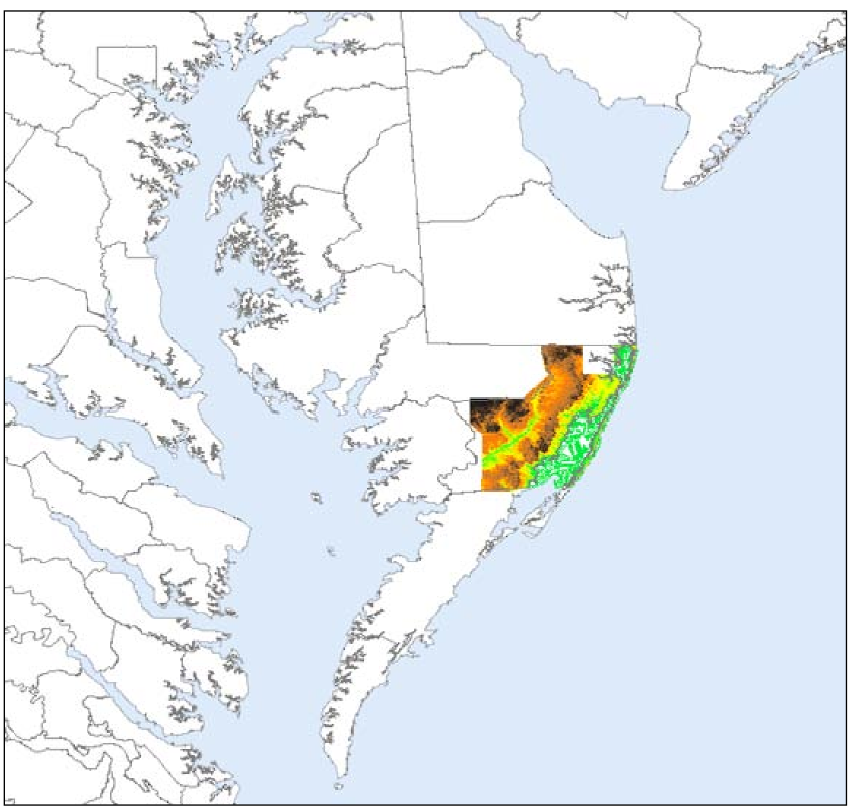

Figure 3.26. Worchester County, MD LiDAR Data.

North Carolina Datasets

NCDEM Terrestrial LiDAR Data

High-resolution topographic LiDAR data collected and processed in 2001 by the NCDEM-FPMP were used for land areas. These data were collected as part of NCDEM-FPMP's effort to modernize FEMA Flood Insurance Rate Maps (FIRMs) statewide and in response to the damage caused by Hurricane Floyd in 1999. The data were collected at 5-meter nominal post spacing and referenced to NAD83 North Carolina State Plane horizontal datum and NAVD88, feet vertical datum.

The data were received in ASCII raster format referenced to a horizontal datum of North Carolina State Plane and a vertical datum of NAVD88, feet. The data files were imported into GRASS and re-projected into geographic coordinates, NAD83 using GRASS' r.proj function. An XYZ text file was exported and the vertical units were converted from feet to meters using a Perl script.

National Elevation Dataset (NED)

The 10-meter (1/3 arc-second) USGS NED elevation data (NOAA NED Release Notes 2004) was obtained for the entire DEM area to provide a base layer of data for the DEM. The USGS NED was developed by merging the highest-resolution, best quality elevation data available across the United States into a seamless raster format. The data were downloaded from the USGS seamless data server (http://seamless.usgs.gov/viewer.htm) in geographic coordinates, NAD83, NAVD88 meters, GRID format. The data must be downloaded in pieces so the many GRID files were mosaiced together using the ArcGIS Mosaic to New Raster tool utilizing a 32 bit floating integer option. Figure 3.27 illustrates the extent of this complete Region III NED GRID.

The NED data had erroneous values over the water areas off the coast. As a result, the data needed to be clipped so that the NED was included in the DEM only in areas where no other data was present. To achieve this, a GRASS r.mapcalc function (e.g., "NED_Tile1=if(isnull(Tile1_allbut_ned), NED, null())") was used to fill in areas without any other data available. This also achieved the effect of clipping the data to the individual tiles as defined by the project graticule. Lastly, the data was then written out to an XYZ text file using the GRASS r.stats function.

For western tiles that bordered on the edge of the study area that contained no other data, the Region III NED GRID was clipped to each Tile as defined by the project graticule and exported to an XYZ text file using the Raster2XYZ script in ArcGIS.

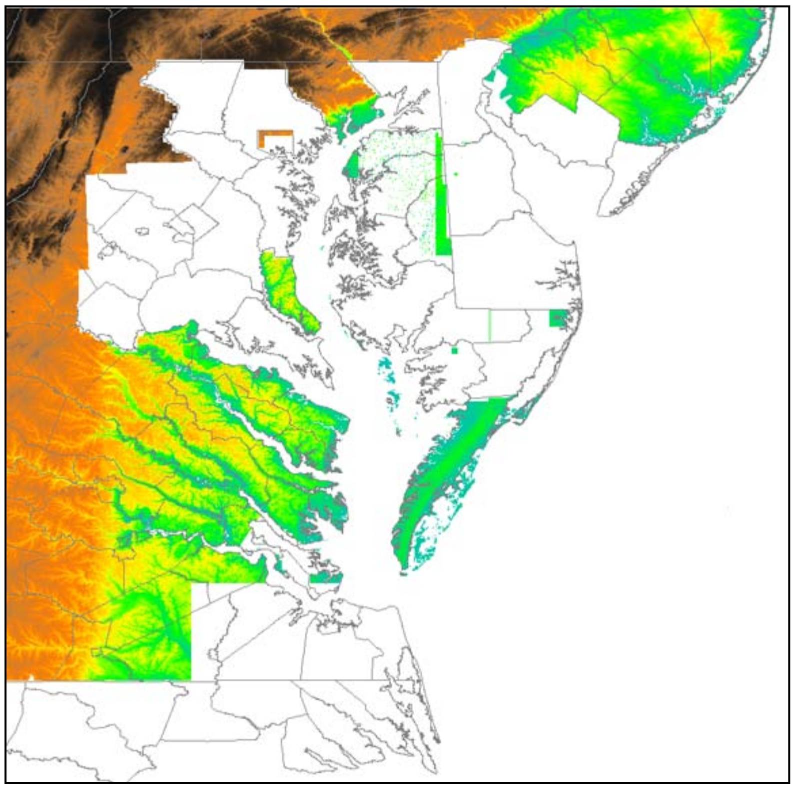

Figure 3.27. National Elevation Dataset Extents.

Establishing Common Datums

Vertical Datum Transformations

Datasets used in the compilation of the Region III DEM were originally referenced to a number of vertical datums including: Mean Lower Low Water (MLLW), Mean Low Water (MLW), Mean High Water (MHW), Mean Sea Level (MSL), and North American Vertical Datum of 1988 (NAVD88). All datasets were transformed to NAVD88 to comply with NFIP standards and develop a hydrodynamic model capable of accurately simulating inundation processes. VDatum was used to confidently perform transformations between the datums. Appendix A shows the datasets and their original vertical datums.

VDatum (Milbert 2002; Parker 2002; Parker et al. 2003) is designed to transform among approximately 30 vertical reference datums. For example, using VDatum, ellipsoidal elevations can be converted, by parametric equations, to elevations relative to NAVD88 using a gridded geoid model such as Geoid03; NAVD88 elevations can be converted to LMSL using a gridded field called the sea surface topography; and LMSL elevations can be converted to elevations relative to other tidal datums, such as MLLW, by using gridded tidal datum fields. VDatum is being developed on a regional basis for the U.S. coastline by the NOS Coast Survey Development Laboratory (CSDL), National Geodetic Survey (NGS), and Center for Operational Oceanographic Products and Services (CO-OPS).

Horizontal Datum Transformations

Datasets used to compile the grid were originally horizontally referenced to NAD83, WGS84, UTM18, or various state plane horizontal datums; the relationships and transformational equations between these horizontal datums are well established. All data were converted to a horizontal datum of geographic coordinates, NAD83, using both the GRASS r.proj function and ArcGIS Project function.

Integrated Topo-Bathy Digital Elevation Model Development

Data Interpolation

Interactive Visualization System (IVS 3D) Fledermaus software was used for the interpolation of data onto each tile. Fledermaus is capable of interpolating and visualizing very large volumes (10's of Gigabytes) of data of numerous types in a single 3D scene with the unique ShiftScape™ rendering engine. The datasets were interpolated at the 0.00011 deg (~10m) cell resolution. A weighted moving average algorithm was used with a search weight diameter of 3-5. The search weight diameter determines how many cells the area of effect will extend over. Essentially the higher the search weight the smoother or more smeared the data will become. See example Figure 3.28 that describes the search weight diameter. Each data tile underwent an iterative process to determine the optimum search weight parameters. A table containing the final interpolation parameters and datasets used for each tile is included as Appendix B.

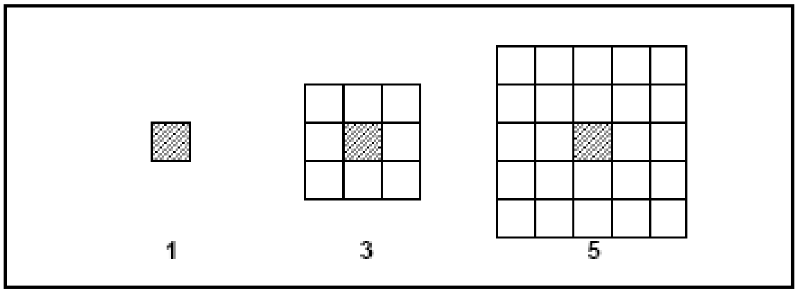

Figure 3.28. Displaying Search Weight Diameter.

Quality Assessment

Visual Inspection and Profile Generation

Throughout the DEM, GRASS module r.slope.aspect (http://grass.itc.it/grass60/manuals/html60_user/r.slope.aspect.html) was used to generate a slope map to allow for visual inspection and identification of artificial slopes along boundaries between datasets. Figure 3.29 provides an example of how the aspect view was used to look for slope anomalies across the seams and within the data. The 0 m contour (land/water interface) was also extracted from DEM tiles in a KML format and then visually inspected using Google Earth™ to ensure the correct shoreline representation as shown in Figure 3.30. Profile transects were generated using Fledermaus over certain tiles that contained visual anomalies to assess the vertical differences found between certain datasets. See Figures 3.31 and 3.32 for examples.

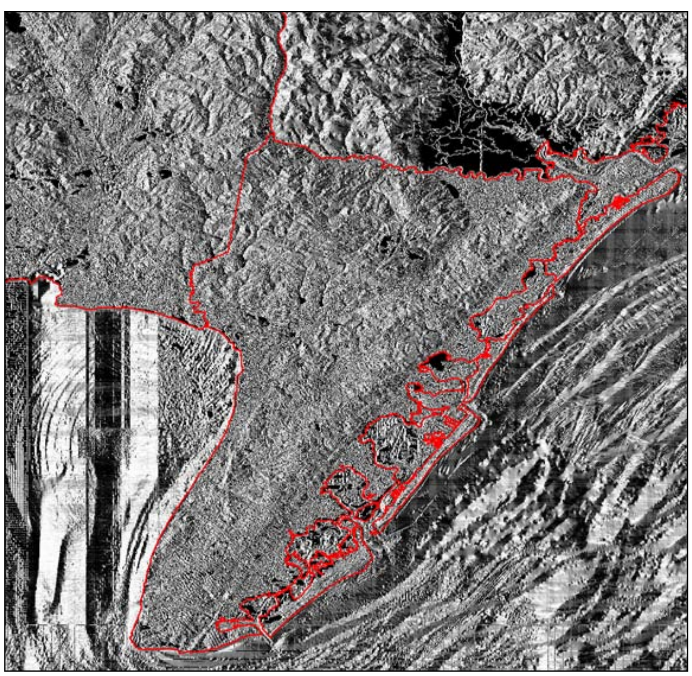

Figure 3.29. Aspect view of Cape May County, NJ.

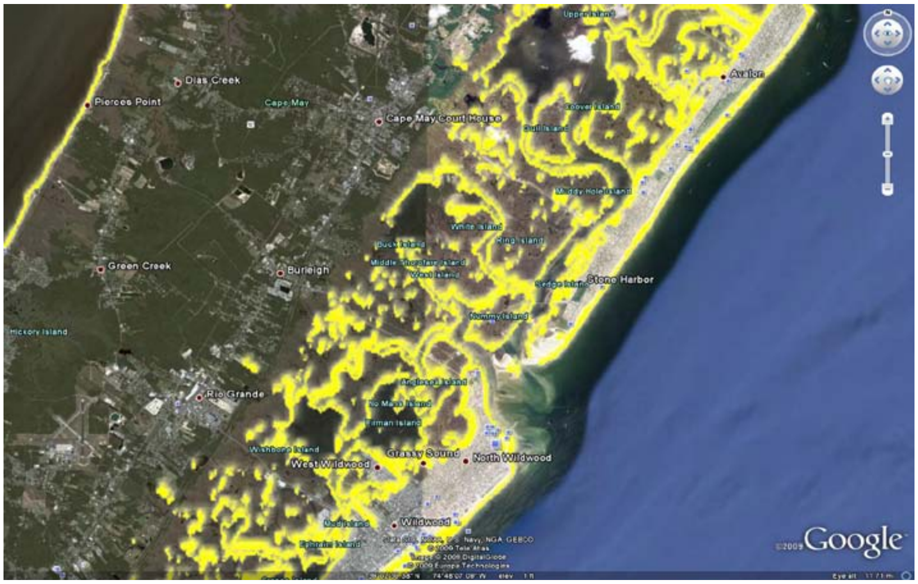

Figure 3.30 Tile 4 Zero meter contour plotted in Google Earth™.

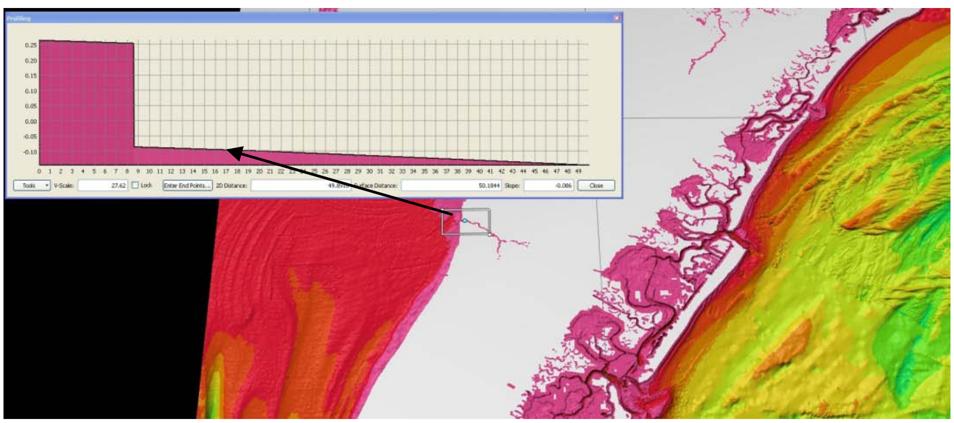

Figure 3.31. Profile transects displaying vertical offsets between data sources.

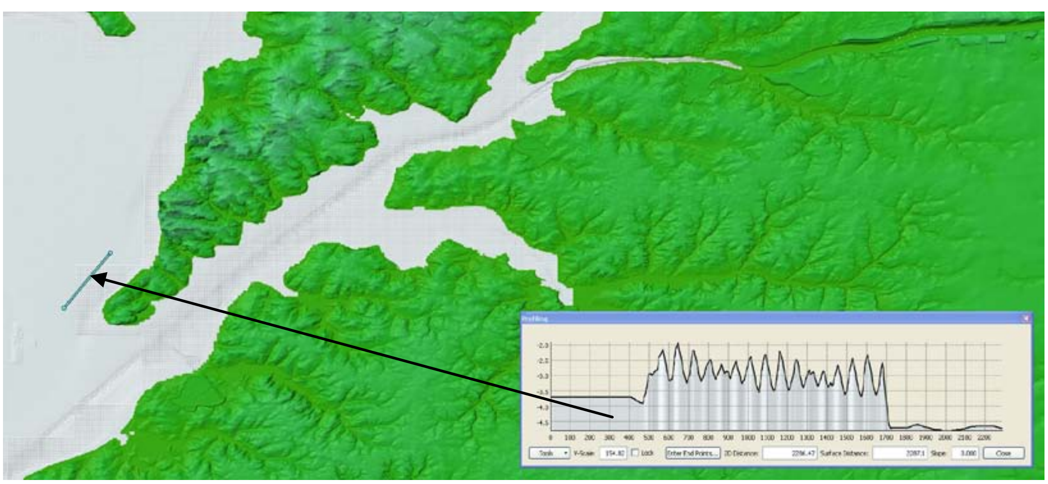

Figure 3.32. Profile transect displaying LiDAR overlapping water (influencing interpolation).

Data anomalies were rectified using techniques that include data clipping, alternative interpolation parameters using Surfer, reprojection, or removal of the dataset from the DEM tile. Bridges were found in certain LiDAR datasets and had to be removed since they served as an impediment to water flow (Figure 3.33). Fledermaus was used to clip the bridges out from the data using a technique called Pure File Magic (PFM). Fledermaus PFM can extract a subsection of data (vicinity of the bridge) and then render as an editable 3D point cloud shown in Figure 3.34. The bridge could then be deleted and the points re-written to a xyz text file for re-interpolation. Figure 3.35 displays the final result without the bridge.

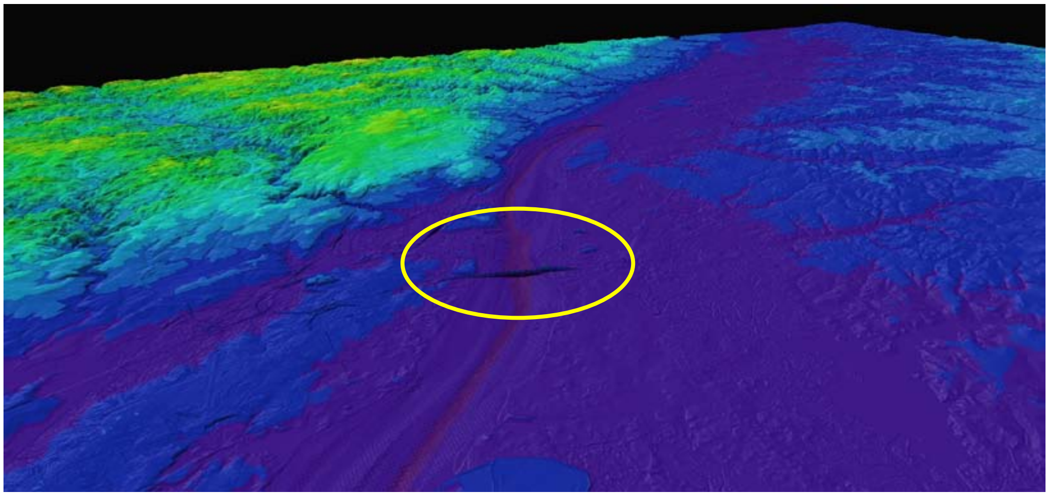

Figure 3.33. Tile 3 displaying Delaware Memorial Bridge.

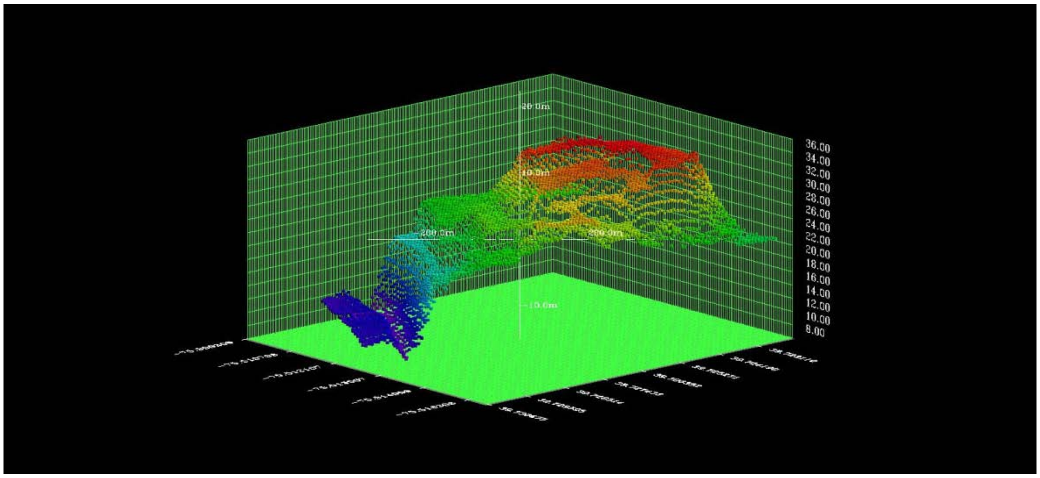

Figure 3.34. Example Fledermaus PFM editable point cloud.

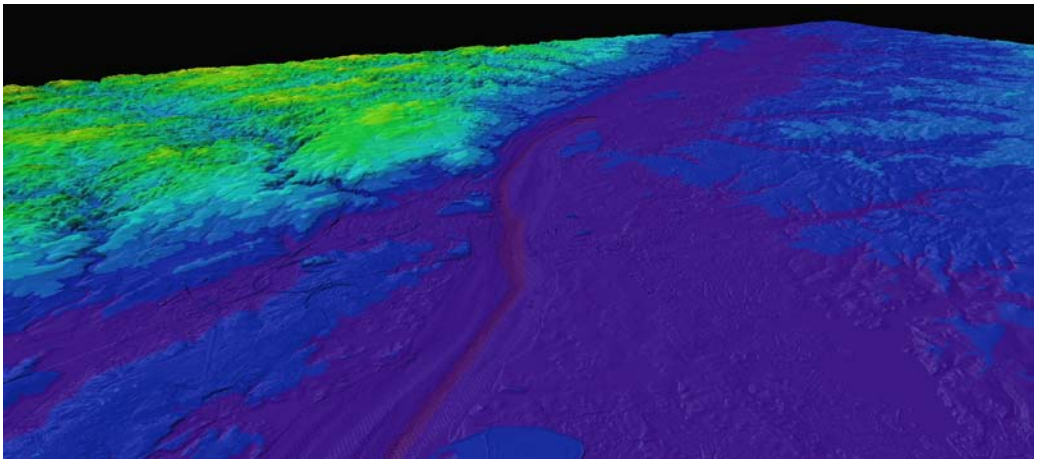

Figure 3.35. Tile 3 Delaware Memorial Bridge removed.

3.5.2 DEM QA/QC Review

The USACE Philadelphia, Baltimore, and Norfolk Districts reviewed the DEM with a similar approach. First, all National Geodetic Survey (NGS) Benchmarks were downloaded that covered each District's region. Benchmarks are permanently fixed marks that establish the exact elevation and position of a spot on the earth. The NGS Benchmarks provide an independently acquired source of elevation data that can be used for comparison. At each NGS Benchmark location a spot elevation was identified on the corresponding DEM. An example appears in Figure 3.36.

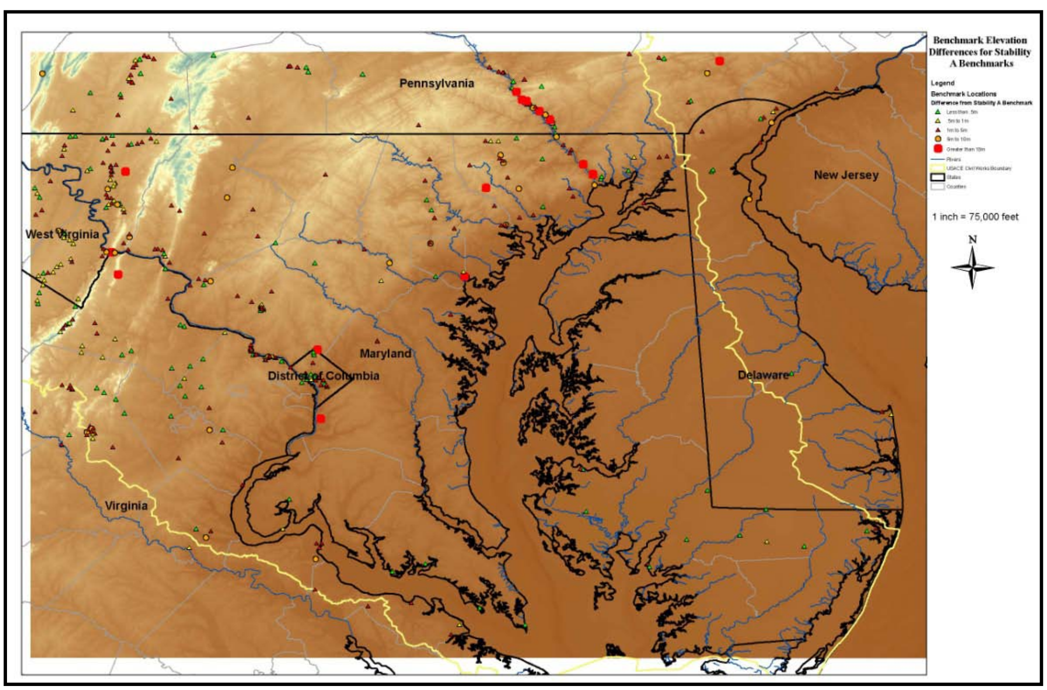

Figure 3.36. Baltimore District NGS Benchmark comparisons to DEM. Colored symbols display elevation variance (see map legend for scale and units).

Next, a mathematical comparison between NGS benchmark elevation and DEM spot elevation was performed and the results were tabulated. Furthermore, a qualitative scan of the entire DEM was performed by an experienced engineer looking for visual anomalies. Regularly spaced cross-section lines allowed the engineer to see the profile lines (elevation vs. distance along the line), which made it easier to find potential issues that may be missed during the visual scan. The Baltimore, Norfolk, and Philadelphia Districts DEM review reports are included as Appendices C, D, and E respectively. The issues raised from the reviews of the USACE Districts were addressed by the DEM team and responses are included as Appendix G.

ARCADIS also performed a thorough review of the DEM. Their analysis consisted of visual inspection between aerial photography and DEM elevations. See example of QA/QC in Figure 3.37 below. The ARCADIS QA/QC document is included as Appendix F.

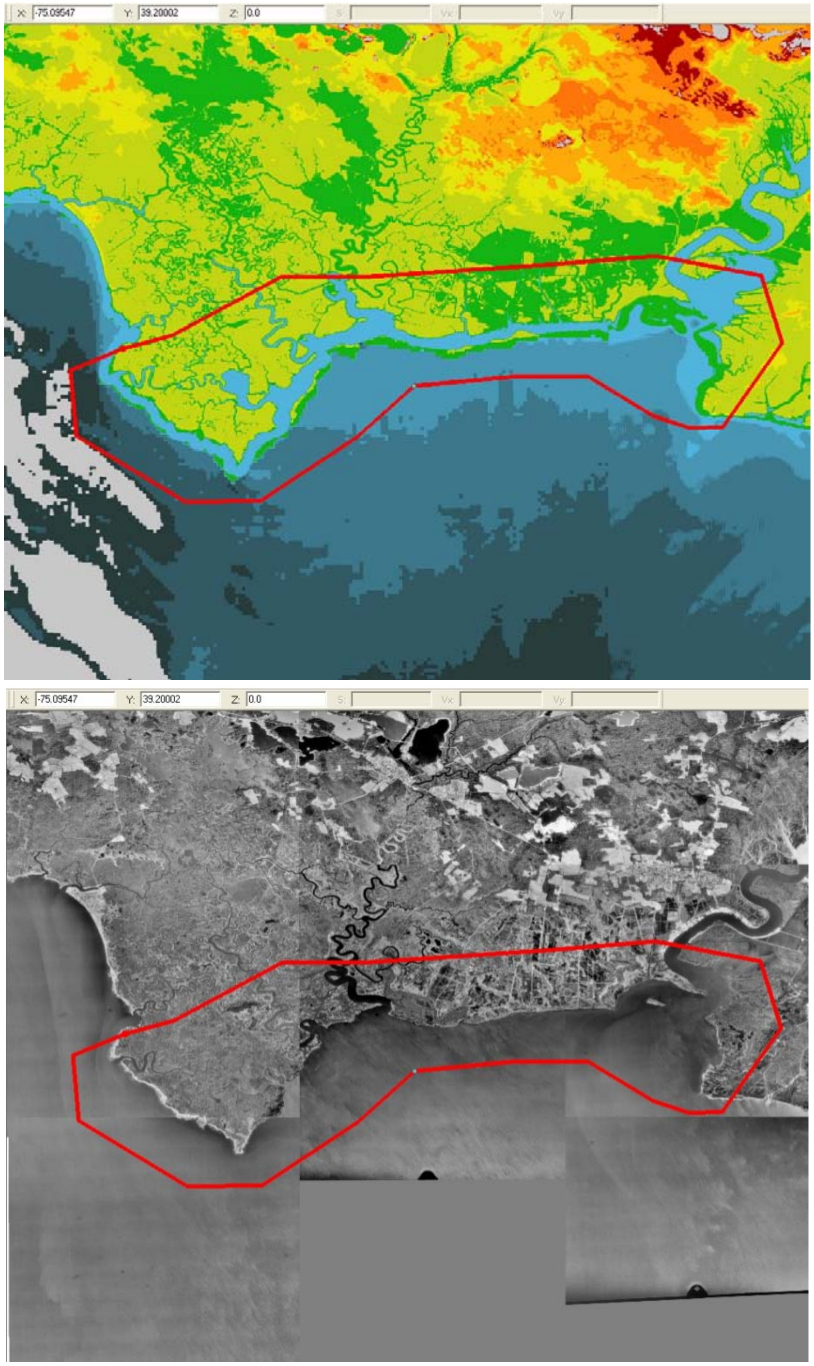

Figure 3.37. ARCADIS QA/QC of Tile 3 displaying false island present in DEM (colored image) and not in Aerial photograph.

4 Summary and Conclusions

An integrated topographic/bathymetric DEM with cell spacing of 1/3 arc-second (~10 meters) of FEMA Region III including the states of North Carolina, Virginia, West Virginia, Maryland, Delaware, Pennsylvania and New Jersey has been developed with revision from Version 1.0. The best available data from U.S. federal agencies, state agencies, and universities were obtained and processed for compilation. The reviews from the USACE Districts and ARCADIS have been addressed and the DEM completed in February 2010 including the additional Tile 3 North Section and is shown as Figure 4.1 below.

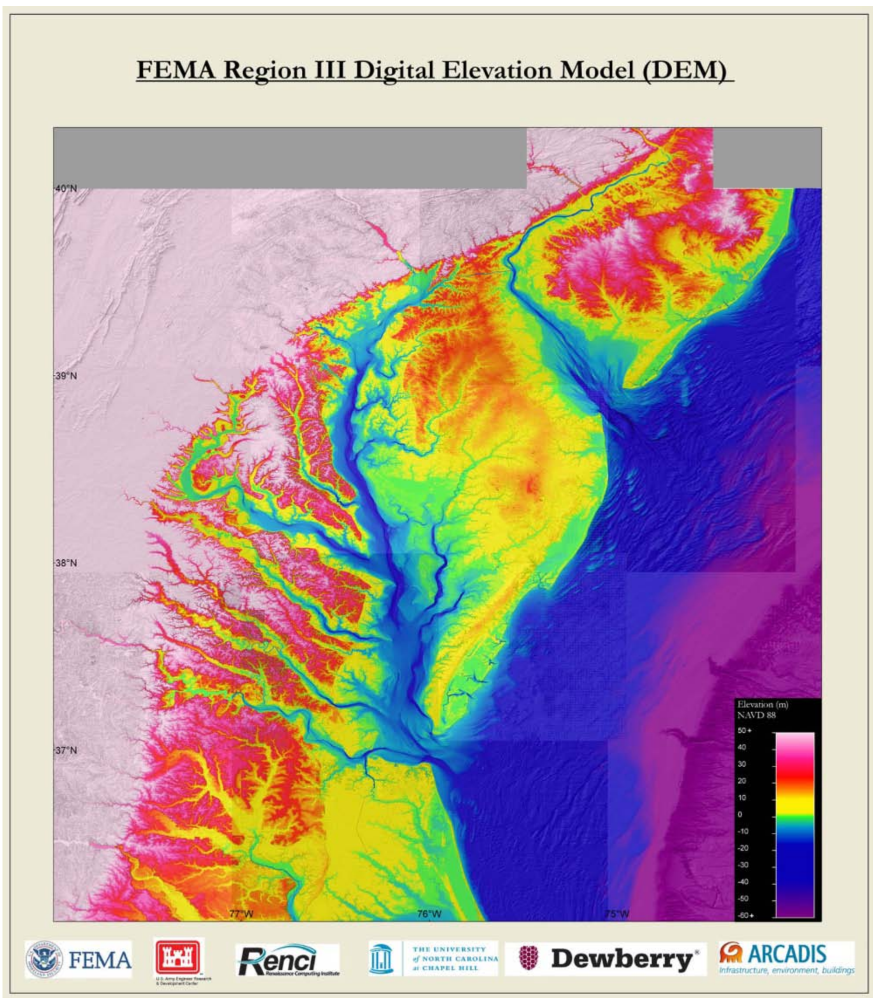

Figure 4.1. FEMA Region III DEM.

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Michael F. Forte, Jeffrey L. Hanson, Lisa Stillwell, Margaret Blanchard-Montgomery, Brian Blanton, Rick Luettich, Hugh Roberts, John Atkinson, and Jason Miller

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Appendices A – G can be found on attached cd.

14. ABSTRACT
The Federal Emergency Management Agency, Region III office, has initiated a study to update the coastal storm surge elevations within the states of Virginia, Maryland, and Delaware, and the District of Columbia including the Atlantic Ocean, Chesapeake Bay and its tributaries, and the Delaware Bay. This effort is one of the most extensive coastal storm surge analyses to date, encompassing coastal floodplains in three states and including the largest estuary in the world. The study will replace outdated coastal storm surge stillwater elevations for all Flood Insurance Studies in the study area, and serve as the basis for new coastal hazard analysis and ultimately updated Flood Insurance Rate Maps (FIRMs). Study efforts were initiated in August of 2008, and are expected to conclude in 2010.

The storm surge study will utilize the Advanced Circulation Model for Oceanic, Coastal and Estuarine Waters (ADCIRC) for simulation of 2-dimensional hydraulics. ADCIRC will be coupled with 2-dimensional wave models to calculate the combined effects of surge and wind-induced waves. A seamless modeling grid was developed to support the storm surge modeling efforts. This report, the second of three reports comprising the required Submittal 1 documentation, provides a detailed overview of the construction of the modeling mesh and the development of an integrated computational system for FEMA Region III storm surge modeling.

15. SUBJECT TERMS
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Delaware Bay
Digital Elevation Model (DEM)
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Renaissance Computing Institute
100 Europa Drive, Suite 540
Chapel Hill, NC 27517

University of North Carolina
Institute of Marine Sciences
3431 Arendell St
Morehead City, NC 28557

ARCADIS
4999 Pearl East Circle, Suite 200
Boulder, CO 80301

Philadelphia District
US Army Corps of Engineers
Wanamaker Bldg, 100 Penn Square East, Philadelphia, PA 19107

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